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IMPROVEMENT OF HIGH-TEMPERATURE PROPERTIES OF MAGNESIUM-CERIUM FORGING ALLOYS

By K. Grube, J. A. Davis, L. W. Eastwood, C. H. Lorig and H. C. Cross

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IMPROVEMENT OF HIGH-TEMPERATURE PROPERTIES OF MAGNESIUM-CERIUM FORGING ALLOYS

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SUMMARY

An investigation was undertaken to obtain an improvement in the high-temperature properties and resistance to creep of magnesium-cerium forging alloys. From preliminary tests, it was decided that the best combination of tensile properties at room temperature and at 600° F, as well as maximum resistance to creep, was produced by the extrusion of a $2\frac{7}{8}$-inch billet to 3/4 inch at 1000° F, at a speed of 4.11 inches per minute, followed by a solution heat treatment and an aging treatment. Also as a result of these tests, a magnesium-cerium-manganese alloy containing 6 percent cerium and 2 percent manganese was chosen as the base composition for the experimental alloys.

The experimental heats were made by minor element additions to this base composition. Tensile properties at 70° and 600° F were then obtained on these experimental alloys, and in addition most of the compositions were subjected to short-time creep tests at 600° F. The tensile properties were apparently improved by the addition of silver, barium, cadmium, nickel, sodium, strontium, or zirconium. Of these elements, nickel had the most outstanding beneficial effect. The most plausible method of improving creep resistance appeared to be the addition of a suitable alloying element. While some elements had a very harmful effect, a number of the fourth element additions, particularly aluminum, improved the creep properties somewhat.

INTRODUCTION

Available data prior to the initiation of this experimental program on magnesium-cerium forging alloys indicated that these alloys possess an unusual combination of low density and relatively high properties for elevated-temperature service up to at least 600° F. (A comparison of the high-temperature properties of magnesium-cerium wrought alloys with those of two wrought aluminum alloys is given in the appendix.) While the magnesium-cerium-manganese alloys have not been widely used, they have been investigated experimentally, and forgings of an alloy similar to the EM-42 type had limited use in Germany during World War II. The EM-42 alloy contains a nominal 4 percent cerium and 2 percent manganese, while EM-62 contains a nominal 6 percent cerium and 2 percent manganese. The cerium content referred to in this report is actually rare-earth content of which approximately one-half is cerium. The objective of the research program was to obtain an improvement in these magnesium-cerium alloys in respect to their elevated-temperature tensile properties and resistance to creep.

The experimental work was concerned with:

(1) The construction of indirect extrusion tools whereby a larger extrusion billet could be used with a given press capacity and a more uniform extruded product would be secured than is obtainable by the usual direct extrusion methods.

(2) The conducting of preliminary tests to determine the proper extrusion temperature, extrusion rate, degree of reduction, and heat treatment to produce optimum high-temperature properties.

(3) The processing and testing of a large number of experimental alloys, using the standard procedure developed under item (2). These experimental compositions were extruded and heat-treated, after which the tensile properties at room temperature and at 600° F were obtained. In addition, most of the compositions were also subjected to a screening-out creep test conducted at 600° F.

Although the magnesium-cerium alloys are fairly difficult to prepare and cast into sound ingots, no development of this phase of the project was required since a satisfactory melting procedure had been previously developed on a project for the Air Materiel Command, Wright-Patterson Air Force Base.

This program was conducted at the Battelle Memorial Institute under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

PROCEDURE AND EQUIPMENT

Melting Procedure for Magnesium-Cerium Alloys

Most of the magnesium-cerium-base alloy compositions were prepared by the melting technique developed on the project previously mentioned.

By this method of melting, the fluid salt fluxes were replaced by dry nitrogen which protected the metal during the melting operation.

Specifically, this melting procedure consists of melting magnesium-cerium scrap and magnesium-base materials first in a steel crucible. If the charge so added to the steel crucible extends above the top, it is necessary to protect the charge, during the initial part of the melting, with Dow 181 reagent. As soon as the charge settles below the crucible top, the crucible is covered and dry nitrogen introduced over the surface of the charge. It is quite possible, of course, to perform the melting operation without loading the crucible above the top so that the entire melting operation can be conducted in a dry-nitrogen atmosphere. After the charge has been melted under the dry-nitrogen atmosphere and the temperature of about 1400° F is reached, the cover is removed and alloy additions made, with Dow 181 reagent used to provide protection against burning. After these alloy additions melt or dissolve and the crucible charge has been stirred to produce a uniform composition, the cover is replaced and the melt reheated to about 1400° F and held for about 30 minutes at 1400° F under the protective nitrogen atmosphere.

The metal is then poured into a preheated steel ingot mold 3 inches in diameter at the bottom, $3\frac{1}{2}$ inches in diameter at the top, and 14 inches deep, with Dow 181 again being used as a protective agent to prevent burning during the pouring operation. Since the melt temperature is high and the ingot mold is preheated to approximately the same temperature, it is possible to hold the melt for about 3 minutes before solidification begins. This provides an opportunity for certain nonmetallic particles to settle to the bottom of the ingot mold. Water is then introduced into the tank holding the ingot mold and, as the water level slowly rises, the ingot solidifies from the bottom upwards.

About 1/2 inch of the bottom of the ingot is sawed off, fractured, and examined to make certain that all the heavy nonmetallic particles are contained in a small volume near the bottom of the ingot. The top of the ingot is cropped off to produce a billet about 10 inches long. This is scalped to $2\frac{7}{8}$ inches in diameter preparatory to extruding.

Since most of the alloys contain 2 percent manganese, this is added in the form of A.S.T.M. M1 alloy melting stock. Accordingly, M1 alloy containing 2 percent manganese was prepared in a separate melting operation. To do this, 3 percent manganese in the form of manganese chloride is added to the commercially pure melt at 1650° F, using a protective covering of Dow 310 flux. After the manganese has been absorbed, the melt is cooled to 1450° F and poured off into ingot molds preparatory to remelting when preparing the experimental alloys. The use of any flux containing manganese chloride must be made in a separate melting operation.

If this is not done, the manganese chloride will react with the cerium and cause a serious loss.

After the scrap magnesium-cerium alloys and magnesium-base material have been melted, as described above, and the melt heated to 1400° F under a protective atmosphere of nitrogen, the cover is then removed, and the cerium as well as the minor elements are added as indicated. The minor element additions were made in a phosphorizer at the same time the cerium addition was made. However, a number of the higher melting-point metals were added to the M1 alloy composition at 1650° to 1750° F in a separate melting operation during which Dow 310 flux could be used for protection. These high melting-point metals could not be added to the magnesium-cerium alloy because the nitrogen atmosphere is not protective at the high melt temperatures required to obtain proper solution of such difficultly soluble elements.

Although a few experimental alloys containing beryllium as a minor element were melted under Dow 220 flux following the recommended commercial practice, this procedure was generally avoided because the Dow 220 did not always separate satisfactorily from the metal, and thus caused flux inclusions.

Extrusion Equipment

The extrusion equipment included a 250-ton press. This press was equipped with indirect extrusion tools and figure 1 shows an assembly drawing of them. In order to reduce the heat loss from the container through the bottom block, 1/8 inch of Transite insulation was placed between the container and the bottom block on which it rested.

The indirect extrusion method was chosen over the direct method because (1) lower maximum pressures are required, thereby permitting the use of a larger extrusion billet for a given press capacity, and (2) the extruded rod is reported to be more uniform from one end to the other because of the manner in which the metal flows from the container through the die.

A photograph of the hydraulic press with the extrusion equipment in place along with two scalped billets is presented as figure 2.

By the indirect extrusion method, the extrusion billet is placed in the preheated container and, as the die at the end of the ram moves downward, the metal is extruded through the hollow ram, and in this instance, up through the top of the press.

Creep Test

The equipment used to obtain the data on the creep properties of the experimental alloys is illustrated by figure 3. Each testing unit is equipped with a chromium-plated copper or steel shell furnace, 6 inches in diameter and 18 inches long, wound with 14-gage Chromel A wire and insulated with silica gel. These furnaces may be used for creep or stress-rupture tests up to 1800° F, but 600° F was the maximum temperature employed in this investigation. A small window is provided at both the front and back of the furnace for measuring the deformation of the test specimen by optical means.

A standard 0.505-inch test specimen and calibration specimen are shown by figure 4. The temperature gradient in the furnace can be controlled and changed by means of external shunts along the tap furnace windings. For this purpose the calibration specimen shown in figure 4 is used, and the furnace is shunted so that the maximum temperature variations measured by thermocouples at positions T_i, C_i, B_i, T_o, C_o, and B_o do not exceed ±3° F at the test temperature. In some cases, even smaller variations are obtained. All temperature variations are kept below the maximum allowed by reference 1. During the actual creep or stress-rupture tests, thermocouples are located at positions T_o and B_o and are used for adjusting the test temperature. Thermocouples are also placed in positions T and B, the control thermocouple at B, and the recorder thermocouple at T. These thermocouples can be replaced while the test is in progress.

The load is applied to the test specimens by means of a lever arm with a 9:1 ratio.

Although stress-rupture tests were not made on this project, the illustrated equipment is fitted with a switch mounted on the lever-arm stop under the lever arm in order to turn off the power to the furnaces and stop the clock when the test specimens break. The clock measures the duration of the test to one-tenth of an hour.

The test temperature of each furnace is maintained by Tag Celectray indicating controllers equipped with a throttling mechanism for closer control. Foxboro controllers with a heater loop anticipating device are also used for the control on some test units. For measurement of deformation, platinum strips are used which are attached to the shoulders of the specimen, one at each end of the gage length. Figure 4 shows the strips in position upon the test specimens. A series of very fine cross marks is ruled on each strip. Changes in length of the test specimen are measured by determining the change in distance between two chosen cross marks, one on each strip.

The microscope, with which deformation readings are made, has an eyepiece fitted with a filar micrometer, and is mounted on a graduated screw. Calibration shows the smallest division of the filar eyepiece to read 0.00005 inch which, on a gage length of about 2.3 inches, provides readings slightly over 0.00002 inch per inch or about 0.002 percent. Deformation readings are usually made daily by two observers.

High-Temperature Tensile Test

The only elevated temperature at which the experimental compositions were tested was 600° F. Briefly, the high-temperature tensile test consisted in placing a specimen in a specially calibrated furnace mounted on the testing machine. The furnace was calibrated so that the temperature variations between seven thermocouples were only $\pm5^\circ$ F. Generally, an even closer temperature range was achieved. Upon reaching the desired temperature, the load was applied at the rate of 0.01 inch per minute per inch of gage length until the 0.2-percent yield strength was reached; the rate was then increased to 0.3 inch per minute per inch of gage length until rupture occurred. All of the bars were stabilized prior to the testing temperature. The stabilized and machined bars were inserted into the furnace, maintained at the testing temperature, and the furnace temperature again brought to equilibrium. This required 20 to 30 minutes after which time the test bar was broken. Stress-strain curves were obtained on each specimen, thus providing the data on proportional limit, modulus of elasticity, and yield strength.

PRELIMINARY TESTS

Before the work on the experimental compositions could be undertaken, it was necessary to determine the optimum extrusion speed, the extrusion temperature, the degree of reduction, and the heat treatment to be employed in the experimental work. It was also necessary to determine which magnesium-cerium-manganese alloy, EM-42 or EM-62, should be used as a base material. These preliminary tests were carried out on alloys containing 4, 6, or 10 percent cerium, with and without manganese, and 18 heats were prepared for this purpose.

The machined billets $2\frac{7}{8}$ inches in diameter and 10 inches long were prepared as described. The billets were then preheated in a furnace containing sulphur dioxide as a protective agent, brought to temperature, and then transferred to the preheated container on the extrusion equipment. This container was heated by the electrical-resistance method using a controller for proper operation. Thermocouples were inserted into the container near the top and bottom, and their temperatures were recorded along with the billet temperature, the speed of extrusion, and the pressure required.

Effect of extrusion rate and temperature.- Standard EM-62 alloy ingots were extruded through a 3/4-inch-diameter die at extrusion rates of 0.72 to 27.3 inches per minute, at extruding temperatures of 1000°, 900°, 850°, 800°, and 750° F. These bars were heat-treated for 3 hours at 1000° F and aged for 16 hours at 400° F; the tensile bars were machined, and room-temperature tensile properties obtained. The results of these tests are listed in table 1 and are graphically represented by figure 5.

As indicated by tables 1 and 2, for a given extrusion rate, the best tensile properties at room temperature and at 600° F were obtained at extrusion temperatures of 900° to 1000° F. The highest tensile and yield strengths and lowest elongations were obtained, for a given extrusion temperature, by the slowest extrusion rate; whereas, the most rapid extrusion rate produced the lowest tensile and yield strengths and the highest elongation values. For this reason, 4.11 inches per minute was the extrusion rate chosen for the balance of the experimental work.

Effects of degree of reduction and of heat treatment.- The effects of extrusion conditions and of heat treatment on the tensile properties at room temperature and the tensile and creep properties at 600° F were investigated by extruding standard EM-62 alloy at 800° and 1000° F through 1/2-inch- and 3/4-inch-diameter dies, at an extrusion speed of 4.11 inches per minute. Each set of specimens was tested after a complete heat treatment and after stabilization only. The solution heat treatment consisted of 16 hours at 1040° F, and the aging treatment was carried out 16 hours at 400° F. The stabilizing treatment performed on the heat-treated bars as well as the as-extruded bars tested at 600° F consisted of 24 hours at 650° F. This stabilizing treatment has been the standard one used on all magnesium-cerium alloys prior to testing at 600° F. The billets extruded through a 3/4-inch-diameter die were given a 93.75-percent reduction; whereas, those extruded through a 1/2-inch-diameter die were given a 97.22-percent reduction.

Samples for each extruding condition and each heat treatment were subjected to tensile tests at room temperature and at 600° F, as well as to creep tests at 600° F. The data obtained on this part of the experimental work are listed in the first 10 lines of table 2, heats A2985, A2986, A3056, and A3057.

While the creep data are not strictly comparable, as indicated by the data in table 2, it will be noted that the room-temperature tensile properties obtained by the higher degree of reduction are not markedly different from those obtained by extruding to 3/4-inch-diameter bar. This is probably contrary to ordinary experience where direct extrusion methods are employed. Had a direct extrusion method been used, it is quite possible that some benefits may have been obtained by the higher reduction. However, with the experimental extrusion methods employed on this project, it is evident that little is gained by the higher reduction by the extrusion process. Furthermore, the use of a 1/2-inch-diameter bar would very seriously complicate the high-temperature tensile tests.

Figure 6 shows the microstructures at 100X of EM-62 alloy given a reduction by extrusions of 85.9, 93.75, and 97.22 percent. While these photomicrographs show that a fairly substantial improvement is obtained in the uniformity of the structure when the reduction is increased from 85.9 to 93.75 percent, a relatively slight increase in uniformity of structure has been obtained by increasing the reduction from 93.75 to 97.22 percent.

Heat treatment has a very marked effect upon the 600° F tensile strength and creep properties; however, the heat treatment has very little effect upon the room-temperature tensile properties. Thus, a comparison of two sets of bars from the same heat in which one set was given a solution, aging, and stabilization treatment, whereas the other was stabilized only, shows that an increase of about 1500 psi in tensile strength is obtained on the bars given the complete heat treatment at 600° F. In addition, the short-time creep tests at 600° F and a 1300-psi load show the minimum creep rate is 0.013 percent per hour for the stabilized material, whereas 0.0005 percent per hour is the minimum creep rate when the same alloy has been solution-heat-treated, aged, and then stabilized. It is obvious, on the basis of these results, that a full solution heat treatment followed by aging was employed on all the experimental compositions. Those bars which were tested either in tension or in creep at 600° F were also stabilized for 24 hours at 650° F.

It was initially thought that the best procedure would be to extrude the $2\frac{7}{8}$-inch-diameter billets to 1-inch squares and then forge these 1-inch squares to 3/4-inch-diameter bar, from which the test specimens could be machined. It was soon discovered, however, that, while this procedure could be carried out, it was rather tedious and slow because the experimental alloys did not necessarily forge very satisfactorily even after the extrusion operation. Therefore, this procedure was abandoned and the $2\frac{7}{8}$-inch-diameter billets were extruded to 3/4-inch-diameter rod which was then heat-treated and subjected to the routine tests.

<u>Effect of cerium and manganese contents</u>.- A heat of EM-42 alloy containing 4 percent cerium and 2 percent manganese was prepared in order to evaluate the desirability of using the EM-42 composition as a

base rather than EM-62. The data on heat A2980 in table 2 show the tensile properties at room temperature and at 600° F as well as some results of the creep tests. Again, a very marked improvement was obtained by the solution heat treatment followed by aging and then stabilization. This improvement is indicated not only by the markedly improved high-temperature tensile strengths but also by the very much lower creep rate. It will be noted from these data that EM-42 and EM-62, heat-treated and aged, produce about the same room-temperature tensile properties and resistance to creep at 600° F. However, at 600° F, the yield strength of EM-42 alloy appears to be about 500 psi lower and the tensile strength about 1000 psi lower than the strengths of the EM-62 composition. Therefore, the EM-62 composition was chosen as a base to which the various experimental additions were made.

A comparison of heats A2857 and A2838 in table 2 shows that an increase in cerium content to approximately 10 percent reduces the elongation, but does not increase the yield or tensile strength markedly at room temperature. At 600° F, both the yield strengths and the ultimate strengths are substantially higher than those obtained by 6 percent cerium. It is remarkable also that this improvement in tensile properties at 600° F is accompanied by a substantial increase in elongation. However, there is a good possibility that such a high cerium content may increase the difficulties of forging; therefore, this high cerium content was not selected as a base for the experimental alloy additions. These improved tensile and yield values warrant further consideration when developing the optimum composition of the magnesium-cerium type of alloy. Data on heats A3225 and A3226 indicate that, on the basis of the tensile data only, the manganese-free alloys have quite favorable tensile properties at room temperature and at 600° F. However, in the absence of manganese, the minimum creep rate of EM-60 alloy is about 16 times higher than when manganese is present. Consequently, no alloy development was based on the EM-60 composition.

Established procedure.- On the basis of the results of the preliminary tests, the following procedure was established as standard:

(1) Ingots were extruded by the indirect method from $2\frac{7}{8}$ inches in diameter to 3/4 inch at a ram speed of 1/4 inch per minute, corresponding to about 4 inches of extrusion per minute, and at a billet and container temperature of 900° to 1000° F.

(2) Extruded 3/4-inch bar was heat-treated 16 hours at 1040° F and aged 16 hours at 400° F. The portion of extruded bar subjected to tests at 600° F was also given a stabilizing treatment consisting of 24 hours at 650° F.

(3) With a few minor exceptions, all of the experimental alloy additions were made to a base composition consisting of 6 percent cerium and 2 percent manganese.

(4) After heat treatment, all extrusions were machined, tensile properties obtained at room temperature and at 600° F, and creep data secured from tests conducted at 600° F and a 1300-psi load.

EXPERIMENTAL MAGNESIUM-CERIUM ALLOYS

One hundred and nine experimental magnesium heats were made, most of which had a base composition of 6 percent cerium and 2 percent manganese. Usually also the minor additions were made in quantities of 0.1, 0.5, and 2 percent. Lesser amounts were added when the solubility of the third element in the liquid was low. The single minor element additions included:

Aluminum	Cobalt	Molybdenum	Tantalum
Silver	Columbium	Sodium	Tellurium
Arsenic	Copper	Nickel	Titanium
Boron	Chromium	Phosphorus	Thallium
Barium	Iron	Antimony	Vanadium
Beryllium	Germanium	Lead	Tungsten
Bismuth	Indium	Tin	Zinc
Calcium	Potassium	Silicon	Zirconium
Cadmium	Lithium	Strontium	

The composition of all the experimental alloys prepared and data on their tensile properties at room temperature and 600° F are listed in table 2. In addition, the results of the short-time creep tests are also listed on many of the alloy compositions, but this portion of the testing is not yet completed.

The experimental alloys containing minor element additions of silver, barium, cadmium, nickel, sodium, strontium, and zirconium had tensile properties somewhat higher than EM-62 alloy at 600° F. Additions of nickel resulted in the higher tensile properties at 70° and 600° F. Quantities of 0.1, 0.5, and 2.0 percent nickel produced a marked improvement in the tensile strengths and yield strengths at 600° F, and quite satisfactory tensile properties at room temperature were also obtained. On the basis of these data, the yield strength is raised about 2500 psi and the tensile strength about 3000 psi at 600° F. However, in view of the possibility of some experimental variations, these results need to be verified before complete acceptance. The effect of sodium was particularly interesting in that it caused extreme brittleness and low properties at room temperature, but fairly high tensile properties were obtained at 600° F. Because of the increase in ductility of this alloy, the tensile properties were actually higher at 600° F than they were at room temperature.

As indicated by the comparative data obtained from the literature and on this project on the relative high-temperature properties of aluminum- and magnesium-base alloys, it is evident that the magnesium-cerium wrought alloys have excellent tensile properties, but in comparison with cast alloys have rather poor resistance to creep at 600° F. Minor additions of barium, bismuth, beryllium, calcium, cadmium, lead, tellurium, and aluminum may have produced a minor improvement in the creep properties of EM-62 extrusion at 600° F. Aluminum, at least in the initial tests, is outstanding so far in that it produced about a tenfold reduction in the average minimum creep rate in the standard creep test. Figure 7 illustrates typical time-deformation curves showing (1) a comparison of EM-42 and EM-62, (2) the effect of heat treatment, (3) a harmful (2.4-percent-cadmium) addition, and (4) a beneficial (0.5-percent-aluminum) alloy addition. Some elements, of which cadmium is outstanding, have a very harmful effect on resistance to creep.

It was thought possible that, since among wrought light alloys a fine-grain material has a markedly poorer resistance to creep than a similar composition having coarse grain, some effort should be made to produce a coarser-grain extrusion. Two methods were investigated in an effort to increase the grain size as follows:

(1) Cold-rolling the extrusion a small amount prior to the solution heat treatment. Such small cold reductions followed by a high-temperature anneal frequently produce a relatively coarse grain.

(2) Using a prolonged heat-treating period at 1040° F, at which temperature grain growth would normally be expected to occur, at least slowly.

Neither of these methods of producing an increase in grain size was particularly successful, and it is concluded that the improvement in creep properties must be brought about by alloy additions.

HIGH-TEMPERATURE OXIDATION OF MAGNESIUM-CERIUM ALLOYS

Creep tests on magnesium-cerium casting alloys conducted on another project (reference 2) showed that, at least during periods of high humidity, prolonged exposure to 700° F produced a very marked scaling of the alloy with preferential attack of the cerium-rich phase in the alloy. Such oxidation would, of course, seriously limit the use of magnesium-cerium alloys, and it was also noted that this attack was much less though still serious after exposure for prolonged periods at 600° F.

There are, in general, two reasonably practical ways of improving the resistance of these alloys to oxidation. These methods are as follows:

(1) By means of an alloy addition, a protective film may be formed, preventing further oxidation. While there is no obvious example whereby this principle is applied in light-alloy metallurgy, it is well known that silicon, chromium, or aluminum added to certain ferrous materials will greatly increase their resistance to oxidation by virtue of the surface film formed. Beryllium in both aluminum and magnesium melts is an example whereby the protective film produced by the beryllium reduces oxidation of the molten metal.

(2) Chemical coatings applied to the magnesium-cerium alloy may be protective and, thereby, increase the resistance of the alloy to oxidation.

Both methods have been investigated. The possibility of using the first method was examined by testing all of the heat-treated, machined test bars of all experimental alloys fractured at room temperature, including all compositions up to heat A3275. These machined test bars were exposed to oxidation at 700° F for 900 hours. In addition to these, machined cast test bars were subjected to various types of coatings, and coated and uncoated samples were also exposed to the 700° F atmosphere at the same time. Data on the chemical coatings are listed in table 3, and the data on the experimental test bars and on the coated and uncoated cast samples are listed in table 4. On the basis of these results, the following conclusions are made:

(1) Extrusions scale and oxidize more than castings of the EM-62 composition.

(2) A reduction in cerium content, the elimination of manganese, or the addition of 0.5 or 2.0 percent aluminum or 1.0 percent silicon eliminates the scale formed on the EM-62 extrusions exposed 900 hours at 700° F, but does not adequately reduce oxidation of the cerium-rich constituent adjacent to the surface.

(3) Only the fluosilicic-acid treatment has markedly reduced the oxidation attack of the cerium-rich phase at the surface of the cast EM-62 specimen. This coating has not been tried on an extrusion of this alloy.

SUMMARY OF RESULTS

The results from the investigation of magnesium-cerium alloys may be summarized as follows:

1. Eighteen heats of magnesium containing 4, 6, or 10 percent cerium, with and without manganese, were made to establish the best base compositions for the experimental work and to determine the best extrusion and heat-treating conditions to employ. As a result of this portion of the work, a base composition consisting of 6 percent cerium and 2 percent manganese was chosen for additions of the fourth element. The extrusion of a $2\frac{7}{8}$-billet to 3/4 inch at 1000° F and a speed of 4.11 inches per minute followed by a solution heat treatment and an aging treatment produced the best combination of tensile properties at room temperature and at 600° F, as well as maximum resistance to creep. Alloys tested at 600° F were also subjected to a stabilizing treatment consisting of 24 hours at 650° F prior to testing. It was found that the heat-treating and aging operation greatly improved the resistance to creep as compared with that obtained by a stabilizing treatment only.

2. One hundred and nine experimental magnesium alloys containing 6 percent cerium, 2 percent manganese, and a fourth element addition were prepared. After the extrusion and heat-treating operations, tensile and creep bars were machined from the extrusion product, and tensile properties at 70° and 600° F were obtained on all the experimental heats. In addition, short-time creep tests at 600° F and a load of 1300 psi were carried out on over one-half of the experimental compositions. It was found that the tensile properties of the EM-62 composition at 600° F were apparently improved by the following single element additions: Silver, barium, cadmium, nickel, sodium, strontium, or zirconium. Of these elements, nickel had the most outstanding beneficial effect.

3. Since the creep resistance of the magnesium-cerium-manganese wrought alloys is markedly inferior to that of similar compositions in cast form, considerable emphasis was placed upon the attainment of better resistance to creep. Efforts to improve creep resistance by increasing the grain size of the extrusions were unsuccessful. As a result, the most plausible method of improving creep resistance appeared to be the addition of a suitable alloying element. While some elements had a very harmful effect, a number of the fourth element additions, particularly aluminum, improved the creep properties somewhat. It was found that aluminum reduces the creep rate in the standard test to about

one-tenth of the value which is obtained without aluminum. The effect of aluminum needs further investigation, however, to determine the optimum composition and the precise amount of the beneficial effects obtained.

4. Experimental work on cast alloys carried out on another project (reference 2) indicates that magnesium-cerium alloys are oxidized very severely when they are exposed to long periods at temperature of 700° F or even at 600° F. There is some indication that this oxidation is more severe when the humidity is high. This oxidation will, of course, seriously limit the application of magnesium-cerium alloys because of the surface attack. The two most promising methods of reducing this surface oxidation are by (a) alloy additions and (b) the application of chemical coatings, preferably those which do not markedly change the dimension. Both methods of reducing surface oxidation were investigated and it was found that, when exposed for 1000 hours at 700° F, EM-62 extrusions oxidize more readily than castings, and that 0.5 or 2.0 percent aluminum or 1.0 percent silicon added to EM-62 extrusions reduced the scaling somewhat. A fluosilicic-acid coating, described in table 3, markedly reduced the oxidation of the magnesium-cerium constituent in cast EM-62 alloy, but this coating has not yet been tried on extruded alloys.

Battelle Memorial Institute
Columbus, Ohio, Aug. 12, 1947

APPENDIX

COMPARISON OF MAGNESIUM-CERIUM WROUGHT ALLOYS WITH TWO WROUGHT ALUMINUM ALLOYS

A comparison of the magnesium-cerium wrought alloys with two wrought aluminum alloys, 18S-T and 32S-T, which are sometimes used for forgings for high-temperature applications, is given in the following discussion. Information on the high-temperature properties of aluminum alloys is taken from reference 3 and the high-temperature properties of magnesium-cerium wrought alloys are taken largely from reference 4. Figures 8, 9, and 10 show a comparison of the effects of temperature on the tensile strength, yield strength, and percentage of elongation, respectively, of the two wrought aluminum alloys, 32S-T and 18S-T, and the two magnesium-cerium wrought alloys, EM-62 and EM-42. Alloy EM-62 contains a nominal 6 percent cerium and 2 percent manganese, whereas alloy EM-42 contains a nominal 4 percent cerium and 2 percent manganese. The cerium, of course, refers to the rare-earth content rather than the cerium content which constitutes approximately one-half of the rare earths present.

In order to differentiate clearly between the data on the aluminum alloys and the magnesium alloys, the magnesium alloys are represented by solid lines; whereas, the aluminum alloys are represented by dashed lines in these figures. It will be noted that, at temperatures up to and including 300° F, the properties of the aluminum alloys are somewhat superior. At 400° F, the properties of the aluminum alloys drop quite rapidly with the result that, at this temperature and at 500° and 600° F, the tensile properties of the wrought magnesium-cerium alloys are substantially superior to the two aluminum alloys commonly used as forgings for high-temperature applications.

There are practically no comparable data available on the effect of temperature on the fatigue properties of the two aluminum and two magnesium-cerium alloys.

There are available some data on the effects of temperature on the creep properties of the four alloys being considered. It is quite difficult to make reliable comparisons because the creep tests are not always conducted under comparable conditions, particularly when the data are obtained in two different laboratories. Furthermore, in some instances, the initial deformation is subtracted from the elongation so that curves representing total elongation against load are not comparable. Some of the existing data on the creep properties of EM-62, EM-42, 18S-T, and 32S-T are indicated in table 5. This table shows the creep rate of the various alloys at various temperatures and loads. The listed average creep rate is for the interval 48 to 96 hours of exposure to the test. This is a rather short time of exposure, and many alloys do not obtain their minimum creep rate during this interval. It is well known that grain size, at least in the wrought aluminum alloys, has a very large effect on the creep properties since the creep rate for a given loading condition will increase markedly with decreasing grain size. This is probably true of the magnesium-cerium alloys also, and this is one factor not usually reported for the creep data. Another factor is the effect of stabilization. It will be evident from the data in table 5 that a stabilized magnesium-cerium alloy has a higher creep rate than an unstabilized alloy exposed to the same conditions of temperature and load. This effect of stabilization is another factor which makes creep-rate data difficult to compare when they are obtained in different laboratories or under different conditions. If the magnesium-cerium alloys listed in table 5 had been heat-treated, their creep properties would have been better. In view of the effects of stabilization, grain size, heat treatment, and possibly other factors, the data in table 5 are not comparable to a high degree. However, there are some indications that the magnesium-cerium wrought alloys have somewhat higher creep rates under the listed conditions of load than the aluminum alloys, 18S-T or 32S-T.

Data obtained at Battelle show a comparison of creep rates of cast and wrought EM-62 as follows:

Alloy and conditions	Temperature (°F)	Load (psi)	Duration of test (hr)	Total deformation (percent)	Minimum creep rate (percent/hr)
EM-62 heat-treated, aged, and stabilized, cast	600	2500	100	0.18	0.0007
EM-62 heat-treated, aged, and stabilized, extruded	600	2500	113	.27	.0380

Table 6 shows a comparison of the creep properties of cast and wrought 142 and EM-62 alloys taken from references 3 and 4. It will be noted from these data that the wrought aluminum alloys were only slightly inferior to the same composition in cast form. On the other hand, at a load of 2200 psi, the wrought EM-62 alloy at 500° F has a creep rate 10 times that of the same composition in the cast form, but at a temperature 100° F higher.

In general, cast EM-62 in the heat-treated, aged, and stabilized condition at 600° F and a 2500-psi load has a creep rate similar to that of extruded EM-62 in the heat-treated, aged, and stabilized condition at 600° F, but at only a load of 1300 psi. The importance of improving the creep properties of magnesium-cerium alloys is therefore evident.

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TABLE 1.– EFFECT OF EXTRUSION RATE AND TEMPERATURE ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF EM-62 AND EM-42 ALLOYS

Heat	Melting data: Intended composition: Ce (percent) (a)	Melting data: Intended composition: Mn (percent)	Melting data: Intended composition: Other (percent)	Melting data: Alloying temperature of Ce (°F)	Melting data: Holding time after Ce addition (min)	Melting data: Pouring temperature (°F)	Extrusion data: Reduction (percent)	Extrusion data: Rate (in./min of 3/4-in.-diam. rod)	Extrusion data: Temperature: Ingot (°F)	Extrusion data: Temperature: Container (°F)	Heat treatment (b): Solution: Time (hr)	Heat treatment (b): Solution: Temperature (°F)	Heat treatment (b): Aging time at 400° F (hr)	Grain size, average diameter (in.)	Room-temperature tensile properties: Elongation (percent in 2 in.)	Room-temperature tensile properties: Reduction of area (percent)	Room-temperature tensile properties: Yield strength, 0.2-percent offset (psi)	Room-temperature tensile properties: Tensile strength (psi)
A2465	6	1.9	None	----	--	----	93.75	27.7	950	900	3	1000	16	------	---	---	------	------
A2465-1	6	1.9	None	----	--	----	Sample cut $5\frac{1}{2}$ inches from end of bar extruded first				3	1000	16	------	3.0	3.5	------	32,500
A2465-3	6	1.9	None	----	--	----	Sample cut $22\frac{1}{2}$ inches from end of bar extruded first				3	1000	16	------	4.5	4.4	------	32,750
A2465-4	6	1.9	None	----	--	----	Sample cut $29\frac{1}{2}$ inches from end of bar extruded first				3	1000	16	------	4.0	3.9	------	32,000
A2465 F	6	1.9	None	----	--	----	Sample reduced 93.75 percent by extrusion and forged to a total of 97.22 percent reduction				3	1000	16	------	1.9	3.7	------	35,500
A2465-5	6	1.9	None	----	--	----	Sample cut 43 inches from end of bar extruded first				3	1000	16	------	4.5	5.1	------	29,500
A2465-6	6	1.9	None	----	--	----	Sample cut 50 inches from front, 5 inches from end of extrusion				3	1000	16	------	5.5	5.8	------	29,000
A2981	4	1.9	None	1410	22	1410	93.75	27.7	950	900	3	1000	16	------	7.1	7.6	------	33,750
A2980	4	1.9	None	1420	21	1420	[c]97.22	27.7	950	910	3	1000	16	------	8.4	9.0	------	33,500
A2983-1	6	1.9	None	1400	20	1400	93.75	.72	1000	1000	3	1000	16	------	3.0	---	30,750	35,000
A2983-2	6	1.9	None	1400	20	1400	93.75	3.6	1000	1000	3	1000	16	0.0016	4.3	---	27,500	32,750
A2983-T3	6	1.9	None	1400	20	1400	93.75	8.9	1000	1000	3	1000	16	------	7.0	---	24,000	30,750
A2983-T4	6	1.9	None	1400	20	1400	93.75	27.3	1000	1000	3	1000	16	------	9.8	---	20,000	29,000
A2984-5	6	1.9	None	1400	20	1400	93.75	4.11	900	900	3	1000	16	------	5.0	---	27,500	33,250
A2984-T3	6	1.9	None	1400	20	1400	93.75	8.9	900	900	3	1000	16	------	5.0	---	22,750	30,500
A2984-T4	6	1.9	None	1400	20	1400	93.75	27.3	900	900	3	1000	16	------	8.5	---	18,500	28,250
A2982-5	6	1.9	None	1410	21	1410	93.75	4.11	850	840	3	1000	16	------	8.5	---	19,750	29,500
A2982-3	6	1.9	None	1410	21	1410	93.75	8.9	850	850	3	1000	16	------	8.0	---	17,250	28,500
A2982-4	6	1.9	None	1410	21	1410	93.75	27.3	850	840	3	1000	16	------	8.3	---	18,750	29,500
A3057-5	6	1.9	None	1400	33	1400	93.75	4.11	800	800	3	1000	16	------	6.0	---	17,500	27,750
A3057-T3	6	1.9	None	1400	33	1400	93.75	8.9	800	780	3	1000	16	------	5.5	---	16,750	26,250
A3057-4	6	1.9	None	1400	33	1400	93.75	27.3	800	800	3	1000	16	------	4.8	---	18,250	27,500
A2987-5	6	1.9	None	1400	33	1400	93.75	4.11	750	750	3	1000	16	.0014	6.8	---	16,750	27,500
A2987-T3	6	1.9	None	1400	33	1400	93.75	8.9	750	740	3	1000	16	------	6.0	---	17,000	27,000
A2985-4	6	1.9	None	1400	32	1400	93.75	27.3	750	750	3	1000	16	------	4.5	---	17,500	26,750

[a]Rare-earth content.
[b]No stabilizing treatment.
[c]1/2-in.-diam. bar.

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TABLE 2.- EFFECT OF EXTRUSION TEMPERATURE, EXTRUSION REDUCTION, HEAT

MAGNESIUM-CERIUM FORGING

Heat	Melting data: Intended composition: Ce (percent) (b)	Mn (percent)	Other (percent)	Alloying temperature of minor element (°F)	Time minor element held at temperature (min)	Alloying temperature of Ce (°F)	Holding time after Ce addition (min)	Pouring temperature (°F)	Extrusion data: Reduction (percent)	Rate (in./min of 3/4-in.-diam. rod)	Temperature: Ingot (°F)	Container (°F)	Heat treatment: Solution: Time (hr)	Temperature (°F)	Aging time at 400° F (hr)	Stabilizing (c): Time (hr)	Temperature (°F)	Grain size, average diam. (in.)
A2985T	6	1.9	--------	----	----	1400	32	1400	93.75	4.11	1000	1000	--	----	----	24	650	0.0014
A2986	6	1.9	--------	----	----	1400	32	1400	93.75	4.11	1000	1000	--	----	----	24	650	------
A2986T	6	1.9	--------	----	----	1400	32	1400	[d]97.22	4.11	1000	1000	--	----	----	24	650	------
A2985TA	6	1.9	--------	----	----	1400	32	1400	93.75	4.11	1000	1000	16	1040	16	24	650	.0006
A2986A	6	1.9	--------	----	----	1400	32	1400	93.75	4.11	1000	1000	16	1040	16	24	650	------
A2986TA	6	1.9	--------	----	----	1400	32	1400	[d]97.22	4.11	1000	1000	16	1040	16	24	650	------
A3057A	6	1.9	--------	----	----	1400	33	1400	93.75	4.11	800	800	16	1040	16	24	650	------
A3056	6	1.9	--------	----	----	1400	30	1400	93.75	4.11	800	800	--	----	----	24	650	------
A3056T	6	1.9	--------	----	----	1400	30	1400	[d]97.22	4.11	800	800	--	----	----	24	650	------
A3056TA	6	1.9	--------	----	----	1400	30	1400	[d]97.22	4.11	800	800	16	1040	16	24	650	------
A2980	4	1.9	--------	----	----	1420	21	1420	93.75	4.11	950	950	--	----	----	24	650	------
A2980A	4	1.9	--------	----	----	1420	21	1420	93.75	4.11	960	950	16	1040	16	24	650	------
A2316	[e]6.08	1.79	0.01 B	1400	----	1400	24	1400	93.75	4.11	995	990	16	1040	16	24	650	------
A3059	6	2	.1 Ba	1400	----	1400	38	1400	93.75	4.11	1000	1015	16	1040	16	24	650	------
A3060	6	2	.5 Ba	1400	----	1400	32	1400	93.75	4.11	1000	995	16	1040	16	24	650	------
A2455	[e]5.81	2	.1 Bi	1400	----	1400	22	1420	93.75	4.11	1000	1005	16	1040	16	24	650	------
A3201	6	2	.5 Bi	1390	----	1400	26	1400	93.75	4.11	1000	975	16	1040	16	24	650	------
[e]A2457	6.78	1.85	.89 Bi	1400	----	1400	18	1400	93.75	4.11	1000	1015	16	1040	16	24	650	------
A2473	[e]5.02	2	[e]1.92 Cd	1430	----	1430	23	1390	93.75	4.11	1000	1005	16	1040	16	24	650	------
A3204	6	2	1.5 Cd	1270	----	1400	33	1400	93.75	4.11	1000	970	16	1040	16	24	650	------
[e]A2452	[e]5.72	1.85	2.41 Cd	1450	----	1450	20	1330	93.75	4.11	1000	990	16	1040	16	24	650	------
A2451	[e]6.00	2	[e].09 Cu	1460	----	1460	20	1320	93.75	4.11	1000	990	16	1040	16	24	650	------
[e]A2448	6.19	1.93	.60 Cu	1430	----	1430	11	1320	93.75	4.11	1000	980	16	1040	16	24	650	------
[e]A2458	5.82	1.90	.14 In	1440	----	1440	25	1410	93.75	4.11	1000	1010	16	1040	16	24	650	------
[e]A2459	5.94	1.84	.61 In	1420	----	1420	24	1420	93.75	4.11	1000	945	16	1040	16	24	650	------
A3058	6	2	.1 Pb	1400	----	1400	40	1400	93.75	4.11	1000	980	16	1040	16	24	650	------
A2461	[e]5.52	2	[e].54 Pb	1450	----	1400	20	1400	93.75	4.11	1000	1010	16	1040	16	24	650	------
[e]A2462	6.48	1.73	2.12 Pb	1400	----	1400	21	1410	93.75	4.11	900	940	16	1040	16	24	650	------
A2463	[e]5.43	2	[e].05 Sb	1460	----	1460	22	1420	93.75	4.11	1000	970	16	1040	16	24	650	------
A2464	[e]5.06	2	[e].10 Sb	1450	----	1450	21	1420	93.75	4.11	1000	925	16	1040	16	24	650	------
[e]A2466	3.77	1.76	.40 Sb	1450	----	1450	22	1420	93.75	4.11	1000	990	16	1040	16	24	650	------
A2450	[e]5.92	2	[e].11 Sn	1430	----	1430	20	1420	93.75	4.11	1000	1005	16	1040	16	24	650	------
A2453	[e]5.86	2	[e].56 Sn	1430	----	1430	21	1420	93.75	4.11	1000	1010	16	1040	16	24	650	------
A3205	6	2	2.0 Sn	1420	----	1420	34	1420	93.75	4.11	1000	950	16	1040	16	24	650	------
A2445	[e]6.08	2	[e].03 Si	1500	----	1430	10	1330	93.75	4.11	1000	985	16	1040	16	24	650	------
[e]A2446	5.77	1.67	[e].03 Si	1500	----	1430	--	1330	93.75	4.11	1000	975	16	1040	16	24	650	------
A3202	6	2	.1 Te	1400	----	1400	32	1400	93.75	4.11	1000	1020	16	1040	16	24	650	------
A3203	6	2	.5 Te	1400	----	1400	29	1400	93.75	4.11	1000	970	16	1040	16	24	650	------
A2467	[e]5.71	2	[e].09 Tl	1430	----	1430	23	1420	93.75	4.11	1000	980	16	1040	16	24	650	------
[e]A2468	5.69	1.76	.44 Tl	1380	----	1380	17	1380	93.75	4.11	1000	1000	16	1040	16	24	650	------
A2444	[e]5.94	2	.11 Zn	1430	----	1430	21	1320	93.75	4.11	1000	1035	16	1040	16	24	650	------
A3061	6	2	.5 Zn	1430	----	1430	40	1400	93.75	4.11	1000	990	16	1040	16	24	650	------
[e]A2449	5.73	1.81	1.49 Zn	1390	----	1390	22	1400	93.75	4.11	1000	990	16	1040	16	24	650	------
[e]A2479	5.69	1.69	.14 Zr	1430	----	1430	20	1420	93.75	4.11	1000	1005	16	1040	16	24	650	------
A2478	[e]6.09	2	[e]<.01 Be	1630	----	1420	21	1420	93.75	4.11	1000	1010	16	1040	16	24	650	------
A2480	[e]5.95	2	[e]<.01 Be [e]<.05 Cd	1440	----	1440	21	1410	93.75	4.11	980	980	16	1040	16	24	650	------
A2630	[e]9.50	2	[e]<.01 Be	1430	----	1420	26	1420	93.75	4.11	980	970	16	1040	16	24	650	------
[e]A2834	5.78	1.85	<.005 Be	1600	----	1420	20	1420	93.75	4.11	1000	995	16	1040	16	24	650	------
[e]A2835	5.73	1.88	<.005 Be	1600	----	1420	20	1420	93.75	4.11	1000	1010	16	1040	16	24	650	------
[e]A2836	5.56	1.93	<.005 Be	1600	----	1420	21	1440	93.75	4.11	1000	1005	16	1040	16	24	650	------
[e]A2837	5.94	1.94	<.005 Be	1600	----	1420	20	1420	93.75	4.11	1000	970	16	1040	16	24	650	------
[e]A2838	5.93	1.61	<.005 Be	Charged in scrap		1400	20	1420	93.75	4.11	1000	1000	16	1040	16	24	650	------
[e]A2857	9.45	1.71	<.005 Be	1600	----	1410	20	1420	93.75	4.11	1000	965	16	1040	16	24	650	------
A3206	6	2	[f].1 Li	1400	----	1400	28	1400	93.75	4.11	800	970	16	1040	16	24	650	------
A3207	6	2	[f].5 Li	1420	----	1420	30	1400	93.75	4.11	900	930	16	800	16	24	650	------
A3208	6	2	[f]2.0 Li	1400	----	1400	32	1400	93.75	4.11	800	Burned in furnace at 800° F ----				--	---	------
A3209	6	2	[f].1 Ca	1400	----	1400	37	1400	93.75	4.11	1000	975	16	1040	16	24	650	------
[e]A2863	3.07	----	--------	----	----	1400	26	1410	93.75	4.11	1000	960	16	1040	16	24	650	------
[e]A2864	3.72	[g].61	--------	1450	----	1450	24	1420	93.75	4.11	1000	995	16	1040	16	24	650	------
[e]A2865	3.80	[g].80	1.34 Zn	1410	----	1410	20	1420	93.75	4.11	1000	990	16	1040	16	24	650	------
[e]A2866	3.71	[g].74	2.17 Zn	1420	----	1420	20	1400	93.75	4.11	800	880	16	800	16	24	650	------
[e]A2977	4.24	[g].60	3.11 Zn	1410	----	1410	23	1410	93.75	4.11	800	995	16	800	16	24	650	------
[e]A2978	4.48	[g].52	5.33 Zn	1430	----	1430	23	1410	93.75	4.11	1000	990	Bar hot short; no good			--	---	------
A3210	6	1.9	[f].5 Ca	1350	----	1350	44	1400	93.75	4.11	900	890	16	800	16	24	650	------

[a]For convenience in tabulation, data for creep rate and tensile properties at 600° F for heats of EM-42 and EM-62 alloys have been included in this table rather than in table 1.
[b]Rare-earth content.
[c]All bars tested at room temperature were not stabilized.
[d]1/2-in.-diam. bars.
[e]Actual analysis
[f]Added.
[g]Zirconium.

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TREATMENT, AND ALLOY COMPOSITION ON THE PROPERTIES OF EXPERIMENTAL ALLOYS AT 70° AND 600° F[a]

Room-temperature tensile properties				Tensile properties at 600° F					Creep rate at 600° F							
Elongation (percent in 2 in.)	Reduction of area (percent)	Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation (percent in 2 in.)	Reduction of area (percent)	Yield strength (psi) 0.1-percent offset	Yield strength (psi) 0.2-percent offset	Tensile strength (psi)	Load (psi)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Final creep rate (percent/hr)	Final total deformation (percent)	Contraction on release of load (percent)
5.0	----	20,250	30,500	136.0	91.6	4750	5500	9,750	----	-----	-----	-------	-------	------	-----
3.5	----	22,750	31,500	-----	----	----	----	------	1300	170	0.018	0.013	0.018	2.60	0.01
5.8	----	24,000	32,750	-----	----	----	----	------	1300	91	.012	.28	.28	23.2	-----
									2500	7.2	.105	4.0	4.0	13.56	-----
3.7	----	23,750	30,500	126.0	89.5	6500	7000	11,250	1300	402	.025	.0005	.00082	.320	.020
1.6	----	22,250	29,500	120.0	----	6500	7000	11,500	1300	884	.016	.00040	.00040	.500	.020
4.3	----	29,500	34,750	-----	----	----	----	------	2500	113	.019	.038	.027	9.26	-----
6.0	----	17,500	27,750	131.0	93.5	5500	6250	9,750	1300	160	.026	.0006	.0006	.182	.018
5.4	----	20,750	29,500	158.0	97.3	3750	4500	7,250	----	-----	-----	-------	-------	------	-----
7.0	----	19,000	29,250	-----	----	----	----	------	----	-----	-----	-------	-------	------	-----
6.5	----	13,250	25,000	-----	----	----	----	------	1300	434	.019	.00070	.00110	.596	.008
7.0	----	19,500	31,000	175.0	99.0	4000	4500	7,750	2500	7.2	.105	4.0	4.0	13.56	-----
9.2	----	19,750	29,250	120.0	86.8	6000	6250	10,250	2500	161	.016	.028	.040	8.26	-----
									1300	619	.025	.00023	.00023	.209	.027
2.3	3.0	27,500	33,000	135.0	75.7	7250	7500	11,250	1300	159	.026	.0015	.0015	.275	.024
4.0	4.9	28,750	34,000	120.8	88.4	7250	7500	11,750	1300	169	.023	.00050	.00050	.164	.020
1.8	2.5	29,250	34,000	133.8	91.1	7750	8000	12,250	1300	144	.024	.00025	.00025	.084	.030
3.5	4.1	26,500	32,750	111.0	81.3	6750	7250	11,500	1300	145	.034	.0012	.0022.	.239	.021
4.5	4.9	27,500	34,250	117.5	88.3	6750	7000	11,250	1300	263	.025	.00025	.00025	.119	.023
6.3	7.0	24,500	33,250	111.5	80.2	6500	6750	11,000	1300	170	.021	.0011	.0011	.243	.018
4.5	4.4	29,500	34,750	103.8	75.5	6250	6500	10,500	1300	166	.023	.0024	.0024	.504	.023
6.0	10.4	24,250	32,000	118.8	85.1	7250	7750	11,000	1300	170	.021	.00030	.00030	.094	.024
2.0	2.7	29,500	34,000	91.0	80.9	7250	7500	11,000	1300	121	.036	.006	.010	.908	.048
3.0	3.7	27,000	32,250	118.5	91.1	6750	7250	11,750	1300	118	.023	.0032	.0032	.438	.023
2.0	1.6	27,750	31,750	164.5	91.4	6500	7000	10,750	1300	123	.021	.0030	.0030	.408	.021
4.3	4.7	27,750	33,750	135.0	87.5	6500	7000	11,500	1300	168	.021	.0010	.0010	.245	.028
4.3	5.4	29,000	35,500	120.0	86.9	5250	5500	10,250	----	-----	-----	-------	-------	------	-----
3.5	4.7	30,500	35,000	122.5	74.5	7250	7500	10,500	1300	192	.019	.00025	.00025	.116	.017
3.8	3.3	25,250	32,500	120.0	77.6	6250	6500	10,250	1300	171	.023	.0005	.0005	.161	.019
6.3	6.4	20,750	29,000	111.0	66.4	5500	6000	10,500	1300	146	.023	.0013	.0013	.267	.019
6.0	4.7	25,000	32,000	133.5	83.5	6500	6750	10,750	1300	141	.032	.0044	.0044	.722	.028
7.0	8.1	21,000	29,500	149.5	82.1	6000	6250	10,000	1300	172	.028	.0010	.0010	.263	.019
8.7	7.3	20,250	29,500	88.0	67.4	6250	6750	10,750	----	-----	-----	-------	-------	------	-----
5.0	5.1	27,000	33,750	121.8	93.1	6500	7000	10,750	1300	143	.030	.0010	.0010	.208	.024
3.5	4.7	27,500	34,500	109.0	90.6	6500	6750	10,750	1300	166	.028	.0011	.0011	.279	.024
6.0	8.9	23,500	32,000	137.5	85.7	6000	6500	9,750	----	-----	-----	-------	-------	------	-----
3.0	3.5	26,250	32,750	139.5	91.7	6750	7000	11,500	1300	142	.030	.0024	.0024	.466	.025
3.0	3.9	25,750	32,500	144.0	92.1	6750	7250	11,500	1300	167	.023	.0014	.0014	.314	.022
2.8	2.0	28,250	33,750	118.5	84.0	6500	7000	11,500	1300	171	.025	.0010	.0010	.257	.029
4.5	6.4	27,000	33,750	141.3	88.1	7250	7500	11,750	1300	238	.028	.00027	.00027	.142	.024
4.0	4.9	27,500	34,000	148.5	84.7	6250	6500	10,500	1300	161	.036	.0022	.0022	.432	.034
2.0	2.5	31,000	36,750	105.0	80.6	5500	6000	11,250	1300	144	.025	.0010	.0010	.227	.026
3.8	4.2	30,500	34,250	117.0	92.6	6750	7000	11,500	1300	168	.029	.0034	.0040	.680	.017
1.8	3.1	32,750	35,000	160.0	88.9	6500	7250	11,000	1300	166	.026	.0011	.0011	.271	.015
3.3	4.1	29,000	33,000	140.5	89.4	6750	7250	12,250	1300	166	.030	.0025	.0025	.504	.006
4.3	4.9	27,250	33,750	106.8	84.8	6500	7000	12,000	----	-----	-----	-------	-------	------	-----
2.5	2.7	27,750	34,500	118.8	79.9	6500	7000	11,500	1300	142	.030	.0048	.0059	.856	.017
4.3	3.3	23,250	31,000	126.3	73.6	5750	6250	10,500	1300	169	.024	.0032	.0032	.580	.013
1.8	2.1	30,000	34,000	105.0	71.6	6750	7250	12,500	1300	120	.028	.0014	.0014	.235	.021
4.3	6.8	27,500	33,750	117.5	92.5	7000	7500	11,000	1300	172	.025	.0003	.0003	.114	.017
4.5	5.4	30,000	36,250	110.5	82.6	7000	7250	12,000	1300	161	.021	.0011	.0011	.252	.015
3.8	4.3	29,000	35,000	130.5	78.9	6250	6500	10,250	1300	119	.028	.0083	.013	1.25	.02
4.5	6.2	26,750	34,750	115.0	91.9	6750	7000	11,250	1300	145	.028	.0049	.0068	.834	.024
4.0	5.4	29,500	35,000	118.5	93.4	7000	7250	11,250	1300	163	.027	.00035	.00035	.092	.021
1.3	2.7	30,250	33,000	167.5	95.1	8250	8750	13,250	1300	241	.049	.00075	.00075	.274	.022
3.8	4.9	28,000	33,250	101.3	89.9	7250	7500	11,500	1300	160	.032	.00035	.00035	.120	.015
2.5	2.7	31,750	35,250	180.0	----	4750	5500	9,000	----	-----	-----	-------	-------	------	-----
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5.0	6.8	26,500	33,000	95.0	67.8	7250	7750	10,750	1300	241	.028	.00020	.00020	.122	.032
8.0	9.3	24,250	31,750	122.5	72.5	5000	5250	8,750	----	-----	-----	-------	-------	------	-----
6.3	11.2	29,250	35,250	121.3	86.0	5000	5500	10,500	----	-----	-----	-------	-------	------	-----
10.0	11.2	24,000	32,250	117.5	85.0	5500	6000	11,000	1300	168	.026	.0019	.0019	.350	.024
11.0	12.5	30,000	36,500	173.8	98.9	5250	5750	9,000	----	-----	-----	-------	-------	------	-----
8.0	10.0	28,000	36,250	178.8	95.4	4750	5500	7,750	----	-----	-----	-------	-------	------	-----
Damaged during extrusion			------	-----	----	----	----	------	----	-----	-----	-------	-------	------	-----
3.5	3.3	31,000	35,500	173.0	----	5500	5500	8,000	1300	97	.021	Elongated 4 percent in 24 hr			-----

TABLE 2.- EFFECT OF EXTRUSION TEMPERATURE, EXTRUSION REDUCTION, HEAT

MAGNESIUM-CERIUM FORGING ALLOYS

Heat	Melting data									Extrusion data				Heat treatment					Grain size, average diam. (in.)
	Intended composition			Alloying temperature of minor element (°F)	Time minor element held at temperature (min)	Alloying temperature of Ce (°F)	Holding time after Ce addition (min)	Pouring temperature (°F)		Reduction (percent)	Rate (in./min of 3/4-in.-diam. rod)	Temperature		Solution		Aging time at 400° F (hr)	Stabilizing (c)		
	Ce (percent) (b)	Mn (percent)	Other (percent)									Ingot (°F)	Container (°F)	Time (hr)	Temperature (°F)		Time (hr)	Temperature (°F)	
A3211	6	1.9	[f]2.0 Ca	1400	----	1400	26	1400		93.75	4.11	800	835	16	800	16	24	650	0.0002
A3212	6	1.9	.1 Al	1390	----	1390	32	1400		93.75	4.11	1000	1010	16	1040	16	24	650	------
A3213	6	1.9	.5 Al	1410	----	1410	32	1400		93.75	4.11	1000	1010	16	1040	16	24	650	------
A3214	6	1.9	2.0 Al	1400	----	1400	24	1400		93.75	4.11	1000	975	16	1040	16	24	650	.0018
A3215	6	1.9	.1 Cd	1400	----	1400	30	1400		93.75	4.11	1000	1005	16	1040	16	24	650	------
A3216	6	1.9	.5 Cd	1400	----	1400	32	1400		93.73	4.11	1000	1000	16	1040	16	24	650	------
A3217	6	1.9	.1 Ag	1410	----	1410	31	1400		93.75	4.11	1000	1005	16	1040	16	24	650	------
A3218	6	1.9	.5 Ag	1410	----	1410	30	1400		93.75	4.11	1000	1010	16	1040	16	24	650	------
A3219	6	1.9	2.0 Ag	1410	----	1410	24	1400		93.75	4.11	1000	955	16	1040	16	24	650	.0006
A3225	6	None	None	-----	----	1430	34	1400		93.75	4.11	1000	1005	16	1040	16	24	650	.0016
A3226	4	None	None	-----	----	1400	36	1400		93.75	4.11	1000	995	16	1040	16	24	650	------
A3227	6	1.9	.75 Zr	1400	----	1400	28	1400		93.75	4.11	1000	970	16	1040	16	24	650	.0008
A3228	6	1.9	.50 Zr	Charged in scrap		1400	27	1400		93.75	4.11	1000	995	16	1040	16	24	650	------
A3229	6	1.9	.25 Zr	Charged in scrap		1420	23	1400		93.75	4.11	1000	940	16	1040	16	24	650	------
A3230	6	1.9	.05 Zr	Charged in scrap		1400	38	1400		93.75	4.11	1000	1035	16	1040	16	24	650	------
A3231	6	1.9	[f].1 Na	1400	----	1400	45	1400		93.75	4.11	1000	1000	16	1040	16	24	650	------
A3232	6	1.9	[f].5 Na	1400	----	1400	26	1400		93.75	4.11	1000	1000	16	1040	16	24	650	.0016
A3235	6	1.9	None	-----	----	1400	27	1400		93.75	4.11	1000	1030	16	1040	16	24	650	.0010
A3236	6	1.9	None	-----	----	1410	34	1400		93.75	4.11	1000	1035	16	1040	16	24	650	------
A3236x	6	1.9	None	-----	----	1410	34	1400		93.75	4.11	1000	1035	16	1040	None	24	650	------
A3237	4	1.9	None	-----	----	1410	31	1400		93.75	4.11	1000	1030	16	1040	16	24	650	------
A3238	6	1.9	[f].1 Sr	1400	None	1400	31	1400		93.75	4.11	1000	1010	16	1040	16	24	650	------
A3239	6	1.9	[f].5 Sr	1300	None	1400	31	1380		93.75	4.11	1000	1010	16	1040	16	24	650	------
A3240	6	1.9	[f]1.5 Sr	1380	None	1420	34	1400		93.75	4.11	1000	1000	16	1040	16	24	650	.0006
A3241	6	1.9	.1 Cd	1400	None	1410	31	1400		93.75	4.11	1000	1010	16	1040	16	24	650	------
A3242	6	1.9	.001 W	[h]1700	120	1400	40	1390		93.75	4.11	1000	1020	16	1040	16	24	650	.0014
A3243	6	1.9	.0005 W	Charged in scrap		1410	47	1380		93.75	4.11	1000	1020	16	1040	16	24	650	------
A3244	6	1.9	.001 Mo	[h]1700	120	1400	37	1390		93.75	4.11	1000	1035	16	1040	16	24	650	.0008
A3245	6	1.9	.0005 Mo	Charged in scrap		1400	38	1380		93.75	4.11	1000	1040	16	1040	16	24	650	------
A3246	6	1.8	[f].1 K	1375	None	1400	33	1380		93.75	4.11	1000	1000	16	1040	16	24	650	------
A3247	6	1.9	[f].5 K	1370	None	1400	31	1380		93.75	4.11	1000	990	16	1040	16	24	650	.0010
A3248	6	1.9	2.0 Ni	[h]1700	45	1400	27	1380		93.75	4.11	900	870	16	900	16	24	650	.0005
A3249	6	1.9	.5 Ni	Charged in scrap		1410	39	1390		93.75	4.11	940	960	16	900	16	24	650	------
A3250	6	1.9	.1 Ni	Charged in scrap		1410	32	1390		93.75	4.11	1000	1020	16	1040	16	24	650	------
A3251	6	1.9	.01 B	1350	5	1400	29	1400		93.75	4.11	1000	1005	16	1040	16	24	650	.0008
A3253	6	1.9	.004 B	Charged in scrap		1420	30	1400		93.75	4.11	1000	1020	16	1040	16	24	650	------
A3254	6	1.9	.05 Fe	[h]1700	5	1400	34	1400		93.75	4.11	1000	1010	16	1040	16	24	650	.0010
A3255	6	1.9	.025 Fe	Charged in scrap		1410	32	1400		93.75	4.11	1000	1010	16	1040	16	24	650	------
A3256	6	1.9	1.0 Si	[h]1700	120	1400	38	1380		93.75	4.11	1000	1020	16	1040	16	24	650	.0020
A3257	6	1.9	.5 Si	Charged in scrap		1410	30	1400		93.75	4.11	1000	1015	16	1040	16	24	650	------
A3258	6	1.8	.1 Si	Charged in scrap		1400	33	1400		93.75	4.11	1000	1015	16	1040	16	24	650	------
A3259	6	1.9	[f].1 Ge	[h]1700	15	1430	25	1400		93.75	4.11	940	990	16	1040	16	24	650	.0008
A3260	6	1.9	.05 Ge	Charged in scrap		1400	28	1400		93.75	4.11	1000	1015	16	1040	16	24	650	------
A3264	6	1.9	.001 V	[h]1700	75	1420	29	1400		93.75	4.11	1000	1015	16	1040	16	24	650	.0006
A3265	6	1.9	.0005 V	Charged in scrap		1420	32	1400		93.75	4.11	1000	1015	16	1040	16	24	650	------
A3266	6	1.9	.01 Ti	[h]1700	20	1400	40	1410		93.75	4.11	1000	1020	16	1040	16	24	650	.0015
A3267	6	1.9	.005 Ti	Charged in scrap		1410	26	1400		93.75	4.11	1000	1020	16	1040	16	24	650	------
A3271	6	1.9	1.0 Co	[h]1700	165	1400	33	1390		93.75	4.11	1000	1010	16	1040	16	24	650	------
A3272	6	1.9	.5 Co	Charged in scrap		1410	30	1420		93.75	4.11	1000	990	16	1040	16	24	650	------
A3273	6	1.9	.1 Co	Charged in scrap		1400	28	1420		93.75	4.11	1000	1010	16	1040	16	24	650	------
A3274	6	1.9	.001 Cr	[h]1700	120	1420	36	1390		93.75	4.11	1000	1010	16	1040	16	24	650	------
A3275	6	1.9	.0005 Cr	Charged in scrap		1400	35	1400		93.75	4.11	1000	1025	16	1040	16	24	650	------
A3276-1	6	1.9	None	-----	----	1410	42	1400		[i]85.9	4.11	1000	1030	16	1040	16	24	650	.0016
-2	Extrusion cold-rolled 3 percent before heat-treating					----	--	----		-----	----	----	----	16	1040	16	24	650	.0020
-3	Extrusion cold-rolled 5 percent before heat-treating					----	--	----		-----	----	----	----	16	1040	16	24	650	.0020
-4	Extrusion cold-rolled 8 percent before heat-treating					----	--	----		-----	----	----	----	16	1040	16	24	650	.0010
A3277	6	1.9	.5 Sb	1400	15	1410	35	1400		93.75	4.11	1000	1015	16	1040	16	24	650	------
A3278	6	1.9	1.0 Sb	1300	25	1420	35	1410		93.75	4.11	1000	1015	16	1040	16	24	650	------
A3281	6	1.7	6.0 Cd	1350	2	1350	30	1310		93.75	4.11	1000	985	16	1040	16	24	650	------
A3282	None	1.9	4.0 Cd	1350	33	----	--	1410		93.75	4.11	1000	1030	16	1040	16	24	650	------
A3283	6	1.9	[f].1 P	1250	----	1400	33	1410		93.75	4.11	1000	1015	16	1040	16	24	650	------
A3284	6	1.9	[f].1 As	1350	----	1390	35	1420		93.75	4.11	1000	1030	16	1040	16	24	650	------
A3285	6	1.9	[f].5 As	1380	----	1400	34	1410		93.75	4.11	1000	1010	16	1040	16	24	650	------
A3287	6	1.9	.001 Cb	[h]1750	150	1400	33	1410		93.75	4.11	1000	980	16	1040	16	24	650	------
A3288	6	1.9	.0005 Cb	Charged in scrap		1410	35	1410		93.75	4.11	1000	970	16	1040	16	24	650	------
A3289	6	1.9	.001 Ta	[h]1750	150	1400	30	1420		93.75	4.11	1000	975	16	1040	16	24	650	------
A3290	6	1.9	.0005 Ta	Charged in scrap		1400	32	1430		93.75	4.11	1000	980	16	1040	16	24	650	------

[a]For convenience in tabulation, data for creep rate and tensile properties at 600° F for heats of EM-42 and EM-62 alloys have been included in this table rather than in table 1.
[b]Rare-earth content.
[c]All bars tested at room temperature were not stabilized.
[f]Added.
[h]Minor element added to M alloy in a separate melting operation.
[i]Extruded to 1 by 1 inch, then heat-treated and stabilized.

TREATMENT, AND ALLOY COMPOSITION ON THE PROPERTIES OF EXPERIMENTAL

AT 70° AND 600° F[a] - Concluded

Room-temperature tensile properties				Tensile properties at 600° F					Creep rate at 600° F							
Elongation (percent in 2 in.)	Reduction of area (percent)	Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation (percent in 2 in.)	Reduction of area (percent)	Yield strength (psi) 0.1-percent offset	Yield strength (psi) 0.2-percent offset	Tensile strength (psi)	Load (psi)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Final creep rate (percent/hr)	Final total deformation (percent)	Contraction on release of load (percent)
1.0	2.1	30,250	33,750	140.0	98.8	4250	4750	8,250	1300	40	0.023	Elongated 10 percent in 15 hr			-----
4.0	6.0	32,750	37,000	90.0	92.3	7250	7500	11,500	1300	138	.028	0.00040	0.00040	0.122	0.028
3.0	2.9	25,750	30,750	75.0	80.2	6500	7250	11,500	1300	629	.024	.00006	.00006	.083	.031
									1300	258	.026	.00006	.00006	.045	.032
4.4	5.1	26,750	33,750	93.8	63.8	5000	5500	9,500	1300	117	.028	.00030	.00030	.061	.028
3.3	4.7	34,000	37,250	133.8	92.7	8000	8500	12,750	----	---	-----	-------	-------	-----	-----
3.0	3.7	30,750	35,000	120.0	91.4	7750	8250	12,250	----	---	-----	-------	-------	-----	-----
5.7	5.6	27,000	32,250	143.8	79.1	7750	8250	12,000	1300	144	.024	.0005	.0005	.139	.004
3.8	6.5	31,750	38,250	98.8	90.0	5500	6250	11,250	1300	165	.021	.0004	.0004	.130	.020
3.6	4.5	29,500	35,500	128.8	90.2	5750	6000	10,000	1300	142	.022	.0007	.0007	.154	.007
2.3	3.5	31,500	35,250	100.0	84.9	7500	8000	13,000	1300	142	.024	.0105	.0105	1.66	.02
2.7	3.5	32,750	37,000	93.5	89.2	7500	8000	12,750	----	---	-----	-------	-------	-----	-----
2.6	3.9	30,000	34,750	116.0	90.6	7750	8750	13,000	1300	160	.024	.0007	.0007	1.65	.017
2.6	3.7	30,750	35,500	157.3	90.4	7750	8250	12,250	1300	142	.024	.0018	.0018	.301	.011
.0	.0	------	12,750	68.5	66.3	7500	8250	12,500	1300	162	.022	.0020	.0020	.452	.020
.2	.0	------	10,000	57.5	55.6	8000	8250	11,250	1300	135	.026	.00065	.00065	.165	.026
2.8	5.3	33,750	39,500	104.0	86.8	7500	7500	11,500	1300	191	.024	.00045	.00045	.152	.021
4.0	5.0	33,500	41,000	115.0	91.9	6750	7250	11,000	----	---	-----	-------	-------	-----	-----
2.3	3.3	33,250	37,250	106.3	87.2	7750	8000	12,000	1300	261	.024	.00025	.00025	.140	.013
3.0	3.1	33,000	40,000	120.0	92.3	7500	8000	12,000	----	---	-----	-------	-------	-----	-----
---	---	------	------	-----	----	----	----	------	1300	169	.024	.0013	.0013	.314	.009
2.2	4.1	35,750	39,000	91.3	88.4	7500	7750	11,250	----	---	-----	-------	-------	-----	-----
3.0	3.9	33,500	36,500	105.0	83.5	7750	8250	12,000	1300	185	.028	.00068	.00068	.189	.017
2.9	3.1	31,500	35,750	132.5	93.8	8000	8250	12,500	1300	185	.022	.00020	.00020	.128	.02
1.8	2.7	29,250	32,500	147.5	87.5	7500	8000	12,750	1300	168	.033	.0003	.0003	.121	.009
3.2	4.7	33,250	37,000	103.5	84.9	7750	8000	12,500	1300	142	.022	.0014	.0014	.243	.015
2.0	2.9	37,000	39,250	97.5	89.3	8500	8750	12,250	1300	207	.024	.00015	.00015	.093	.015
3.5	4.1	29,500	38,250	175.0	96.4	6750	6750	10,500	----	---	-----	-------	-------	-----	-----
2.0	4.1	35,500	38,500	101.3	68.6	6750	7000	10,750	----	---	-----	-------	-------	-----	-----
2.3	2.1	26,000	31,500	116.0	63.6	6750	7250	10,750	----	---	-----	-------	-------	-----	-----
2.0	3.3	35,250	38,000	114.3	94.6	7250	7500	11,500	----	---	-----	-------	-------	-----	-----
1.3	1.1	33,500	34,750	106.3	61.7	6500	6750	10,750	----	---	-----	-------	-------	-----	-----
3.0	3.9	35,000	37,500	150.0	96.2	9000	9500	14,500	1300	149	.026	.0026	.0026	.672	.019
3.3	4.1	38,000	39,750	142.5	97.1	9000	9750	14,500	1300	120	.026	.024	.031	3.23	.03
2.0	1.9	38,000	39,250	141.3	90.7	9250	9500	14,500	1300	190	.026	.00074	.00074	.181	.026
2.8	3.1	34,000	37,000	137.3	95.5	7000	7250	11,250	----	---	-----	-------	-------	-----	-----
2.8	1.9	29,750	35,000	131.3	92.0	7000	7250	10,750	----	---	-----	-------	-------	-----	-----
3.0	4.1	34,500	36,750	128.8	93.2	6750	7250	11,250	----	---	-----	-------	-------	-----	-----
1.5	1.9	34,500	37,250	132.5	93.4	6500	7000	10,750	----	---	-----	-------	-------	-----	-----
9.0	9.8	21,000	29,250	96.3	61.8	5000	5500	8,250	----	---	-----	-------	-------	-----	-----
4.5	5.3	29,750	34,500	78.8	63.9	6000	6500	9,750	----	---	-----	-------	-------	-----	-----
3.0	3.9	32,750	35,250	130.0	85.3	7000	7500	12,250	----	---	-----	-------	-------	-----	-----
2.5	2.5	35,000	36,750	127.5	79.3	6500	7000	11,000	----	---	-----	-------	-------	-----	-----
3.3	3.3	35,500	38,000	128.5	94.6	7000	7250	10,750	----	---	-----	-------	-------	-----	-----
2.0	2.5	31,750	35,500	116.5	88.8	7250	7500	12,000	----	---	-----	-------	-------	-----	-----
2.5	2.2	31,250	37,000	106.5	86.9	7250	7750	11,750	----	---	-----	-------	-------	-----	-----
4.3	6.4	29,500	36,750	91.3	75.2	6750	7500	11,500	----	---	-----	-------	-------	-----	-----
1.8	2.3	32,250	35,750	110.0	89.3	7000	7500	11,500	----	---	-----	-------	-------	-----	-----
3.3	5.3	33,000	36,000	171.5	----	7000	7500	12,250	1300	138	.025	.00072	.00072	.158	.025
3.8	5.2	31,750	34,500	120.0	----	7250	7750	12,500	1300	139	.028	.00066	.00066	.209	.012
3.5	4.3	34,750	36,000	119.0	----	7500	8250	12,500	1300	146	.030	.0010	.0010	.231	.024
1.8	3.1	33,750	34,500	128.5	----	7500	8250	11,500	1300	143	.026	.00030	.00030	.117	.019
2.8	3.7	33,750	34,250	126.0	----	7000	7500	11,500	1300	143	.024	.00170	.00170	.312	.030
---	---	------	------	-----	----	----	----	------	1300	167	.021	.00010	.00010	.067	.029
---	---	------	------	75.0	----	6250	7000	11,000	1300	143	.025	.00040	.00040	.106	.027
---	---	------	------	72.0	----	5500	6500	11,000	1300	88	.027	.0011	.0011	.106	Controller failed
---	---	------	------	118.0	----	5000	5750	9,750	1300	138	.025	.0002	.0002	.081	.025
4.0	4.3	29,750	34,000	72.5	----	4500	4750	6,000	----	---	-----	-------	-------	-----	-----
4.8	5.0	34,000	35,250	115.0	----	6250	6500	10,750	----	---	-----	-------	-------	-----	-----
5.3	5.3	31,000	34,500	106.0	----	5750	6250	9,250	----	---	-----	-------	-------	-----	-----
5.0	5.3	23,750	31,500	64.5	----	5000	5500	8,250	----	---	-----	-------	-------	-----	-----
6.8	8.3	32,000	34,500	91.0	----	5750	6250	10,250	----	---	-----	-------	-------	-----	-----
5.0	4.3	30,000	33,500	143.5	----	6250	6750	11,250	----	---	-----	-------	-------	-----	-----
2.8	3.7	29,000	32,750	157.5	----	6250	7000	11,250	----	---	-----	-------	-------	-----	-----
3.8	4.7	34,000	36,500	91.0	----	7000	7500	11,250	1300	163	.028	.0043	.0066	1.01	.02
2.3	3.3	34,000	36,500	115.0	----	7250	7500	11,250	1300	142	.026	.0052	.0052	.788	.034
4.0	5.3	35,500	36,250	100.0	----	7000	7250	11,250	1300	141	.028	.0029	.0045	.550	.016
2.0	3.2	35,750	35,750	78.5	----	7000	7500	10,750	1300	144	.025	.00097	.00097	.220	.017

TABLE 3.— CHEMICAL COATINGS FOR HIGH-TEMPERATURE

PROTECTION OF MAGNESIUM-CERIUM ALLOYS

Sample	Coating	Application of coating and composition	Time and temperature
A3286A,B	Uncoated	------------------------------------	--------------------------------
A3286C,D	Dow No. 9	A. Alkaline degreasing bath: Trisodium phosphate 240 g Sodium carbonate 240 g Distilled water 8.0 liters Cold-water rinse	Bath temperature of 180°-240° F for 5-15 min, using current density of 15 amp/sq ft
		B. Hydrofluoric-acid bath: Hydrofluoric acid 328 ml Distilled water 1.0 liter Cold-water rinse	Bath at room temperature, immersed 5 min
		C. Galvanic anodizing bath: Ammonium sulphate 180 g Sodium dichromate 180 g Ammonium hydroxide 17 ml Distilled water 6.0 liters Cold-water rinse, hot-water dip, dried in an air blast	Bath temperature of 120°-140° F, using current density of 6 amp/sq ft for 30 min
A3286E,F	Dow No. 10	A. Alkaline degreasing bath: Same as Dow No. 9	
		B. Chromium-nitric pickle: Sodium dichromate 85 g Nitric acid 59 ml Distilled water 1.0 liters Cold-water rinse, hot-water dip	Bath at room temperature, immersed 1 min
		C. Dichromate bath: Sodium dichromate 480 g Calcium fluoride 15 g Distilled water 4.0 liters Cold-water rinse, hot-water dip, dried in an air blast	Bath boiling, immersed 30 min
A3286G,H	Treatment R	A. Alkaline degreasing bath: Same as Dow No. 9	
		B. Anodic bath: Sodium hydroxide, 5 percent 421.5 g Distilled water 8.0 liters Cold-water rinse	Bath temperature of 140°-160° F, using current density of 15 amp/sq ft for 30 min
		C. Seal treatment: Sodium chromate 277 g Distilled water 1.0 liter Cold-water rinse, hot-water dip, dried in an air blast	Bath temperature of 170°-180° F immersed 30 min
A3286I,J	Selenium treatment	A. Apply Dow treatment No. 10 complete	
		B. Selenium coating: Selenium dioxide 128 g Sodium hydroxide 92.6 g Distilled water 1.0 liter Cold-water rinse, hot-water dip, dried in an air blast	Bath temperature of 195°-212° F, immersed 40-90 min at pH 7.1 to 7.5, controlled by adding S_eO_2
A3286K,L	Fluosilicic-acid treatment	A. Alkaline degreasing bath: Same as Dow No. 9	
		B. Fluosilicic-acid treatment: Hydrofluosilicic acid 250 ml Distilled water 750 ml Titanium potassium oxalate added to the saturation point Cold-water rinse, hot-water dip, dried in an air blast	Bath at room temperature, immersed 10 min

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TABLE 4.- SURFACE OXIDATION OF EXPERIMENTAL ALLOYS AND COATED AND UNCOATED CAST ALLOYS AFTER EXPOSURE AT 700° F FOR 900 HOURS

Heat	Intended composition	Coating	Surface	
			Visual observation of scale on surface	Microscopic observation, depth of penetration (mm)
A3235	CM-62	None	Very bad	
A3236	CM-62	None	Very bad	
A3237	CM-42	None	Bad	
A2316	EM-62 + 0.01B	None	Very bad	
A3059	EM-62 + 0.1Ba	None	Bad	
A3060	EM-62 + 0.5Ba	None	Very bad	
A2455	EM-62 + 0.1Bi	None	Bad	
A3201	EM-62 + 0.5Bi	None	Bad	
A2457	EM-62 + 0.9Bi	None	Some scale	
A2473	EM-62 + 1.9Cd	None	Very bad	
A3204	EM-62 + 1.5Cd	None	Very bad	
A2452	EM-62 + 2.4Cd	None	Worst	
A2451	EM-62 + 0.1Cu	None	Bad	
A2448	EM-62 + 0.6Cu	None	Very bad	
A2458	EM-62 + 0.1In	None	Very bad	
A2459	EM-62 + 0.6In	None	Bad	
A3058	EM-62 + 0.1Pb	None	Very bad	
A2461	EM-62 + 0.5Pb	None	Very bad	
A2462	EM-62 + 2.1Pb	None	Worst	
A2463	EM-62 + 0.05Sb	None	Very bad	
A2464	EM-62 + 0.1Sb	None	Very bad	
A2466	EM-62 + 0.4Sb	None	Very bad	
A2450	EM-62 + 0.1Sn	None	Very bad	
A2453	EM-62 + 0.6Sn	None	Very bad	
A3205	EM-62 + 2.0Sn	None	Some scale	
A2445	EM-62 + 0.3Si	None	Very bad	
A2446	EM-62 + 0.3Si	None	Very bad	
A3202	Em-62 + 0.1Te	None	Bad	
A3203	EM-62 + 0.5Te	None	Very bad	
A2467	EM-62 + 0.1Tl	None	Very bad	
A2468	EM-62 + 0.4Tl	None	Very bad	
A2444	EM-62 + 0.1Zn	None	Worst	
A3061	EM-62 + 0.5Zn	None	Bad	
A2449	EM-62 + 1.5Zn	None	Bad	
A2479	EM-62 + 0.1Zr	None	Very bad	
A2478	EM-62 + <0.01Be	None	Very bad	
A2480	EM-62 + <0.01Be	None	Very bad	
	<0.05Cd	None		
A2630	EM-102 + <0.01Be	None	Bad	
A2834	EM-62 + <0.005Be	None	Very bad	
A2835	EM-62 + <0.005Be	None	Very bad	
A2836	EM-62 + <0.005Be	None	Bad	
A2837	EM-62 + <0.005Be	None	Bad	
A2838	EM-62 + <0.005Be	None	Bad	
A2857	EM-62 + <0.005Be	None	Very bad	
A3206	EM-62 + 0.1Li	None	Very bad	
A3207	EM-62 + 0.5Li	None	Worst	
A3209	EM-62 + 0.1Ca	None	Bad	
A2863	3Ce	None	No scale	0.35
A2864	3Ce,0.6Zr	None	No scale	.25 to .85
A2865	3Ce,0.8Zr,1Zn	None	No scale	.40
A2866	3Ce,0.7Zr,2Zn	None	Some scale	
A2977	3Ce,0.6Zr,3Zn	None	No scale	.80
A3210	EM-62 + 0.5Ca	None	Very bad	
A3211	EM-62 + 2.0Ca	None	Very bad	
A3212	EM-62 + 0.1Al	None	Bad	
A3213	EM-62 + 0.5Al	None	No scale	.40
A3214	EM-62 + 2.0Al	None	No scale	.50

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TABLE 4.— SURFACE OXIDATION OF EXPERIMENTAL ALLOYS AND COATED AND UNCOATED CAST ALLOYS AFTER EXPOSURE AT 700° F FOR 900 HOURS — Concluded

Heat	Intended composition	Coating	Surface	
			Visual observation of scale on surface	Microscopic observation, depth of penetration (mm)
A3215	EM-62 + 0.1Cd	None	Bad	
A3216	EM-62 + 0.5Cd	None	Very bad	
A3217	EM-62 + 0.1Ag	None	Worst	
A3218	EM-62 + 0.5Ag	None	Worst	
A3219	EM-62 + 2.0Ag	None	Worst	
A3225	6Ce	None	No scale	0.30
A3226	4Ce	None	No scale	.35
A3227	EM-62 + 0.75Zr	None	Bad	
A3228	EM-62 + 0.50Zr	None	Bad	
A3229	EM-62 + 0.25Zr	None	Very bad	
A3230	EM-62 + 0.05Zr	None	Very bad	
A3231	EM-62 + 0.1Na	None	Very bad	
A3232	EM-62 + 0.5Na	None	Very bad	
A3238	EM-62 + 0.1Sr	None	Very bad	
A3239	EM-62 + 0.5Sr	None	Very bad	
A3240	EM-62 + 1.5Sr	None	Bad	
A3241	EM-62 + 0.1Cd	None	Very bad	
A3242	EM-62 + 0.001W	None	Very bad	
A3243	EM-62 + 0.0005W	None	Very bad	
A3244	EM-62 + 0.001Mo	None	Very bad	
A3245	EM-62 + 0.0005Mo	None	Bad	
A3246	EM-62 + 0.1K	None	Bad	
A3247	EM-62 + 0.5K	None	Bad	
A3248	EM-62 + 2.0Ni	None	Very bad	
A3249	EM-62 + 0.5Ni	None	Very bad	
A3250	EM-62 + 0.1Ni	None	Very bad	
A3251	EM-62 + 0.01B	None	Bad	
A3253	EM-62 + 0.004B	None	Bad	
A3254	EM-62 + 0.05Fe	None	Very bad	
A3255	EM-62 + 0.025Fe	None	Very bad	
A3256	EM-62 + 1.0Si	None	No scale	.25
A3257	EM-62 + 0.5Si	None	Bad	
A3258	EM-62 + 0.1Si	None	Very bad	
A3259	EM-62 + 0.1Ge	None	Bad	
A3260	EM-62 + 0.05Ge	None	Very bad	
A3264	EM-62 + 0.001V	None	Very bad	
A3265	EM-62 + 0.0005V	None	Very bad	
A3266	EM-62 + 0.01Ti	None	Very bad	
A3267	EM-62 + 0.005Ti	None	Very bad	
A3271	EM-62 + 1.0Co	None	Bad	
A3272	EM-62 + 0.5Co	None	Very bad	
A3273	EM-62 + 0.1Co	None	Bad	
A3274	EM-62 + 0.001Cr	None	Bad	
A3275	EM-62 + 0.0005Cr	None	Bad	
A3286A	EM-62 Cast	None	No scale	
B	EM-62 Cast	None	No scale	.55
C	EM-62 Cast	Dow No. 9	No scale	.5
D	EM-62 Cast	Dow No. 9	No scale	
E	EM-62 Cast	Dow No. 10	No scale	.4
F	EM-62 Cast	Dow No. 10	No scale	
G	EM-62 Cast	Treatment R	No scale	
H	EM-62 Cast	Treatment R	No scale	.55
I	EM-62 Cast	Selenium treatment	Some powder on surface	.45
J	EM-62 Cast	Selenium treatment	Some powder on surface	
K	EM-62 Cast	Fluosilicic-acid treatment	No scale	Deepest spot 0.2 mm; generally no penetration
L	EM-62 Cast	Fluosilicic-acid treatment	No scale	Deepest spot 0.2 mm; generally no penetration

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TABLE 5.– AVERAGE CREEP RATE, PERCENT PER HOUR DURING 48 TO 96 HOURS OF TEST, OF 32S–T AND 18S–T ALUMINUM ALLOYS AND WROUGHT MAGNESIUM–CERIUM ALLOYS, EM–62 AND EM–42

Alloy	Condition	Testing temperature							
		300° F		400° F		500° F		600° F	
		Load (psi)	Creep rate (percent/hr)	Load (psi)	Creep rate (percent/hr)	Load (psi)	Creep rate (percent/hr)	Load (psi)	Creep rate (percent/hr)
EM–62	As–extruded	12,000 15,000 18,000	0.00004 .00008 .00014						
EM–62	Extruded and stabilized	12,000 15,000 18,000	.00012 .00038	4,000 6,000 8,000	0.00024 .00078 .00340	2200	0.0039		
EM–42	As–forged	15,000 18,000 23,000	.00008 .00010 .00038						
18S–T	Rod; medium grain; not stabilized			15,000 20,000 25,000	.00087 .00209 Failed, 72 hr			2,000 3,000	0.00114 .00139 Failed, 360 hr
[a]18S–T	Not stabilized			2,500 5,000 7,500 12,500	.00008 .00010 .00014 .00050			1,300 1,900 2,500 3,400	.00043 .00104 .00166 .01880
32S–T	Forged; not stabilized					5000 7500	.0030 Discon–tinued, 10 hr	1,300 2,500	[b].0004 Discon–tinued, 29 hr[b]
32S–T	Rod; not stabilized							2,000 3,000	.0002 Discon–tinued, 7 hr
[a]32S–T	Not stabilized			5,000 7,500 10,000 15,000	.00014 .00026 .00040 .00064			1,300 2,500	.00004 .00028

[a]From reference 5; other data from reference 3.
[b]Bars stabilized 83 days before testing.

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TABLE 6.— COMPARISON OF CREEP PROPERTIES OF

CAST AND WROUGHT 142 AND EM-62 ALLOYS

[Data taken from references 3 and 4]

Condition	Load (psi)	Castings: Total deformation (percent)	Castings: Creep rate (percent/hr)	Wrought: Total deformation (percent)	Wrought: Average creep rate (percent/hr) (50–150 hr)	Test conditions
142 — heat-treated and aged						
Not stabilized	1,300	0.002	0.0005(?)	------	-------	100 hr at 600° F
Not stabilized	2,000	.07	---------	[a]0.06	-------	100 hr at 600° F
Not stabilized	2,500	.11	.025	.13	0.085	100 hr at 600° F
Stabilized	2,500	-----	.05	------	-------	100 hr at 600° F
Not stabilized	3,000	.16	---------	[a].3	-------	100 hr at 600° F
Not stabilized	5,000	.45	.49	Failed	-------	100 hr at 600° F
Not stabilized	10,000	.015	.005	------	-------	100 hr at 400° F
Not stabilized	15,000	.025	.012	.034	.015	100 hr at 400° F
Not stabilized	20,000	.065	.034	.15	.123	100 hr at 400° F
EM-62						
Stabilized[b]	2,200	0.076	0.00036	------	-------	100 hr at 600° F
Stabilized[b]	3,000	.188	.00126	------	-------	100 hr at 600° F
Stabilized[b]	4,000	1.630	.01800	------	-------	100 hr at 600° F
Stabilized[b]	2,200	-----	-------	[a]0.40	[a]0.0039	100 hr at 500° F
Stabilized[b]	3,000	-----	-------	[a]2.70	-------	100 hr at 500° F
Stabilized[b]	4,000	.076	.00050	------	-------	100 hr at 500° F
Stabilized[b]	6,000	.454	.00330	------	-------	100 hr at 500° F

[a]Estimated by interpolation.
[b]Extruded alloys recrystallized 16 hr at 850° F. Cast alloys held 16 hr at 600° F prior to test.

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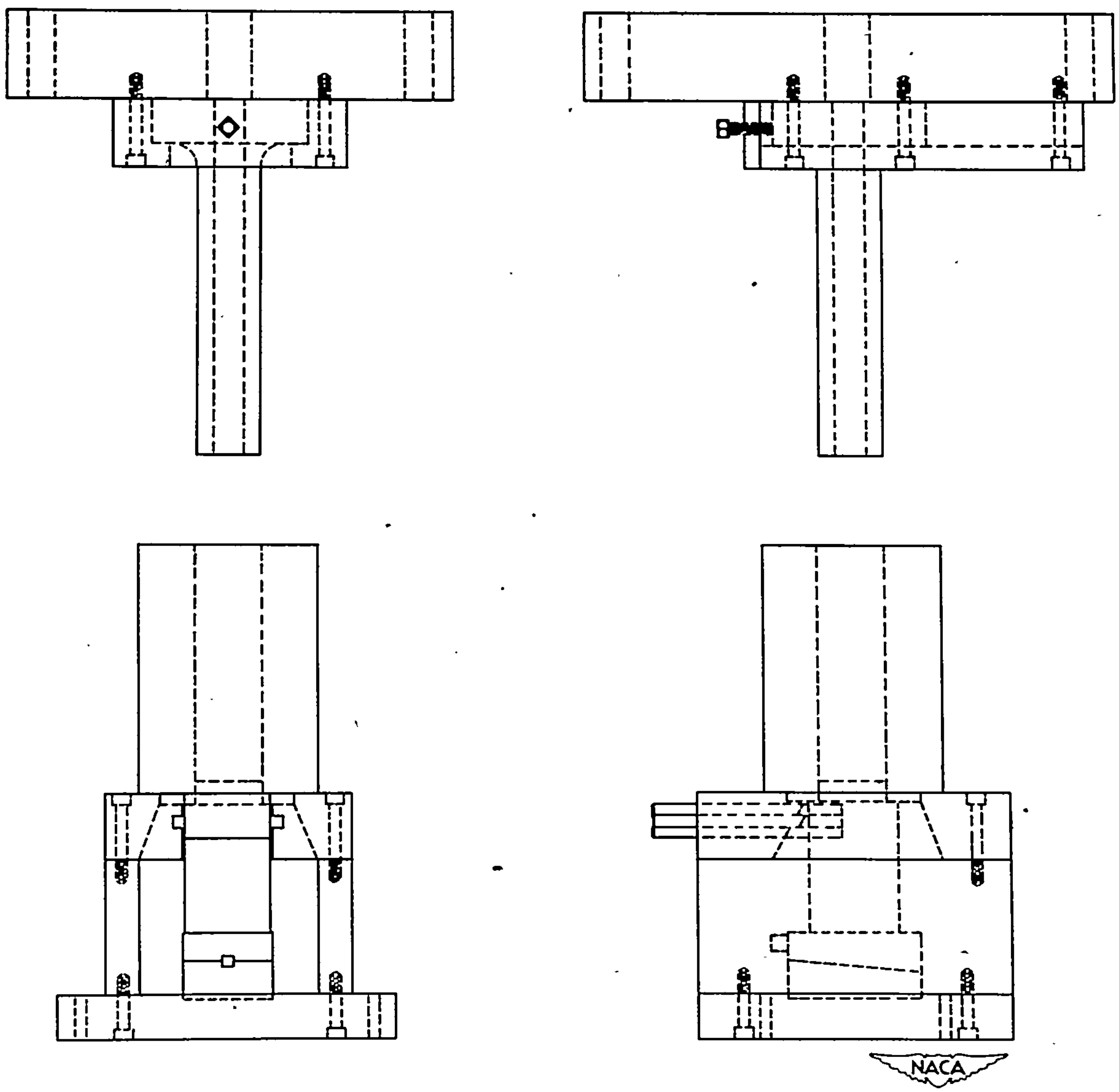


Figure 1.- Assembly drawing of extrusion tools.

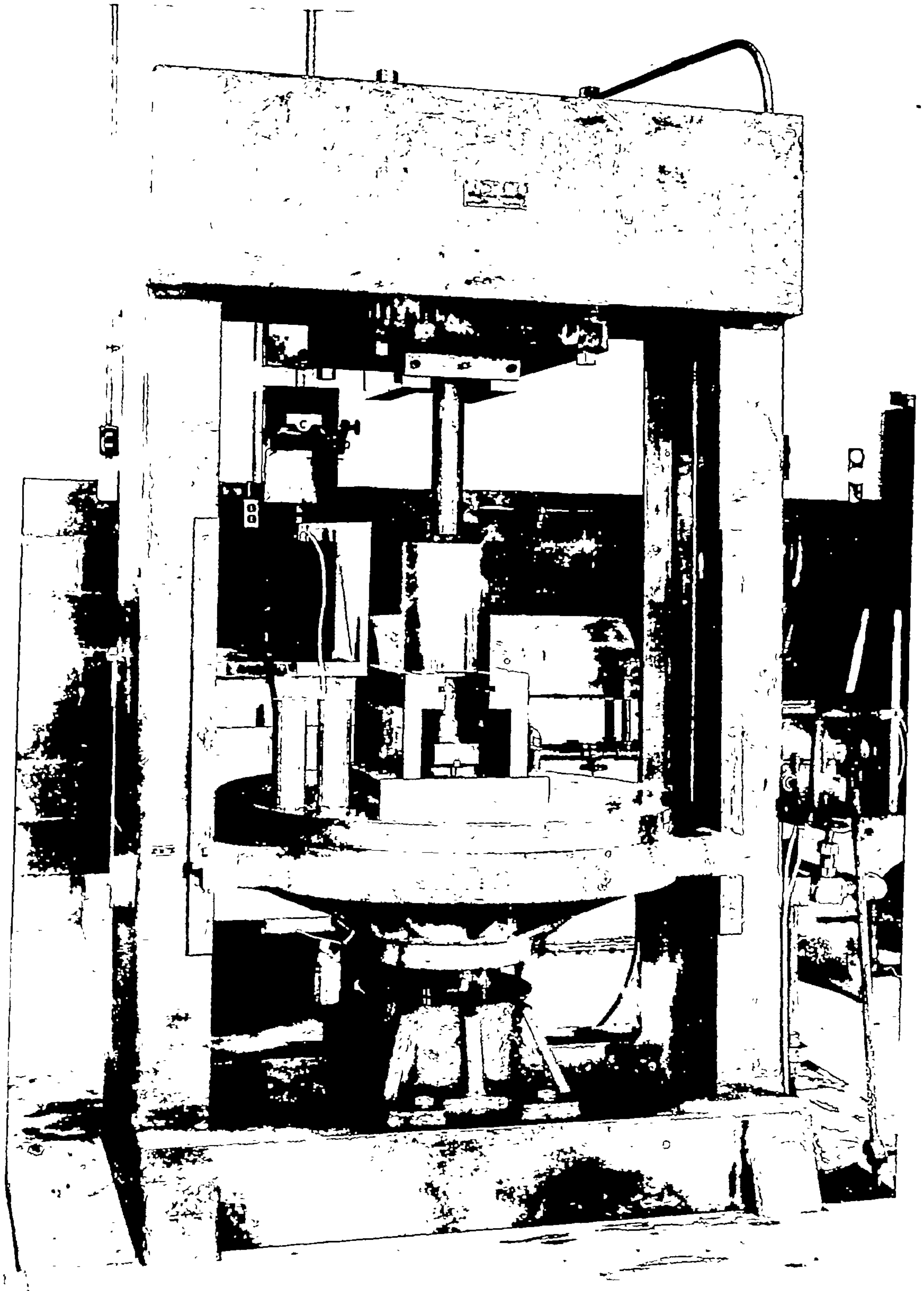


Figure 2.- General view of indirect extrusion press.

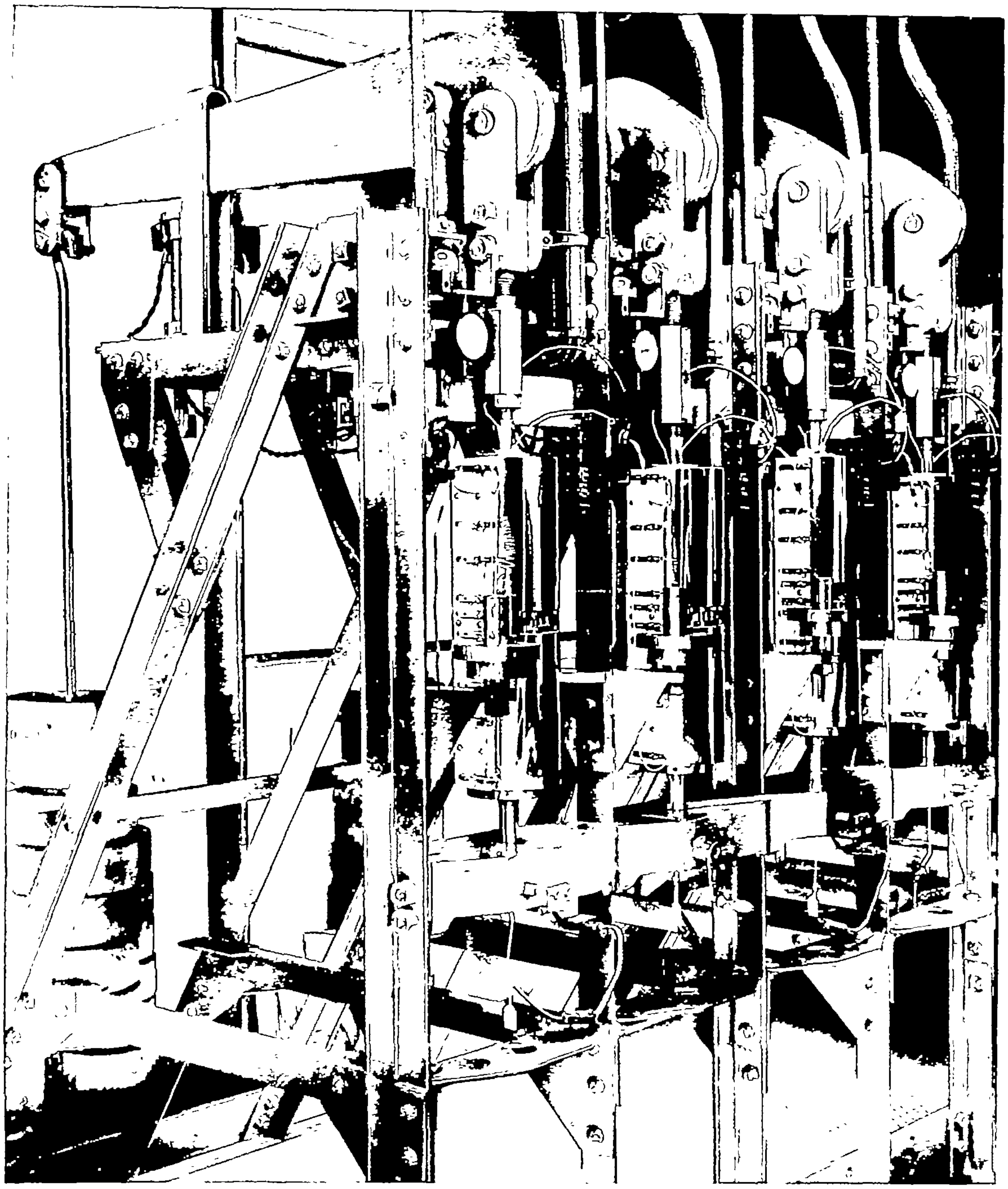


Figure 3.- Battelle creep and stress-rupture units.

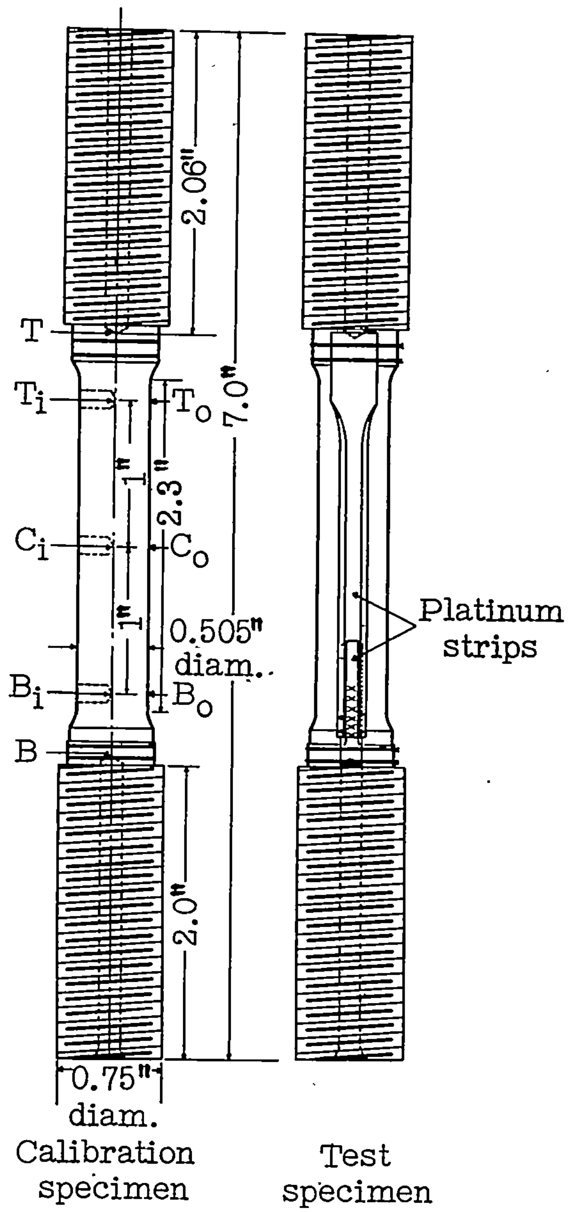


Figure 4.- Calibration and test specimens. Thermocouple positions denoted by T, B, T_i, C_i, B_i, T_o, C_o, and B_o.

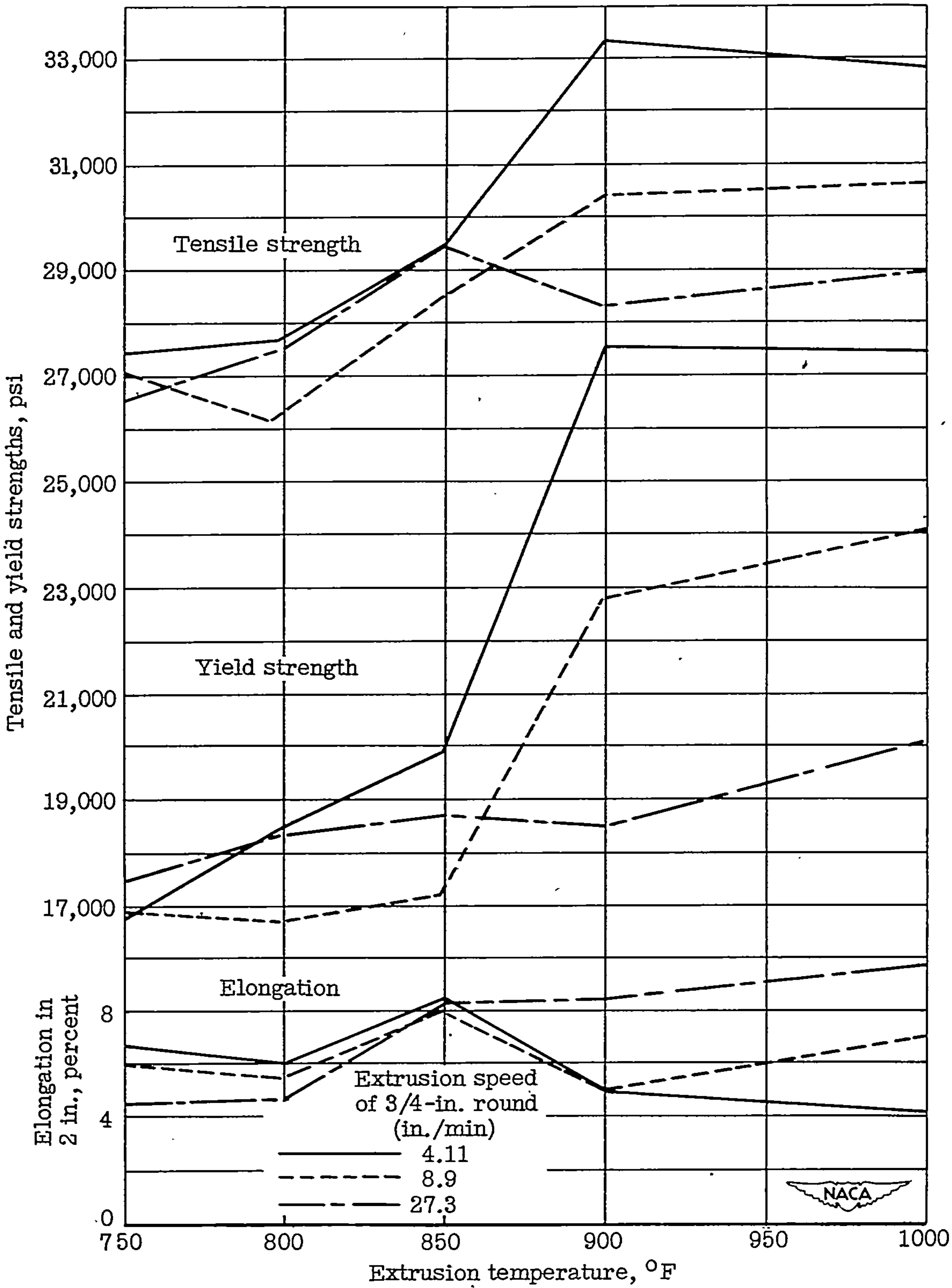
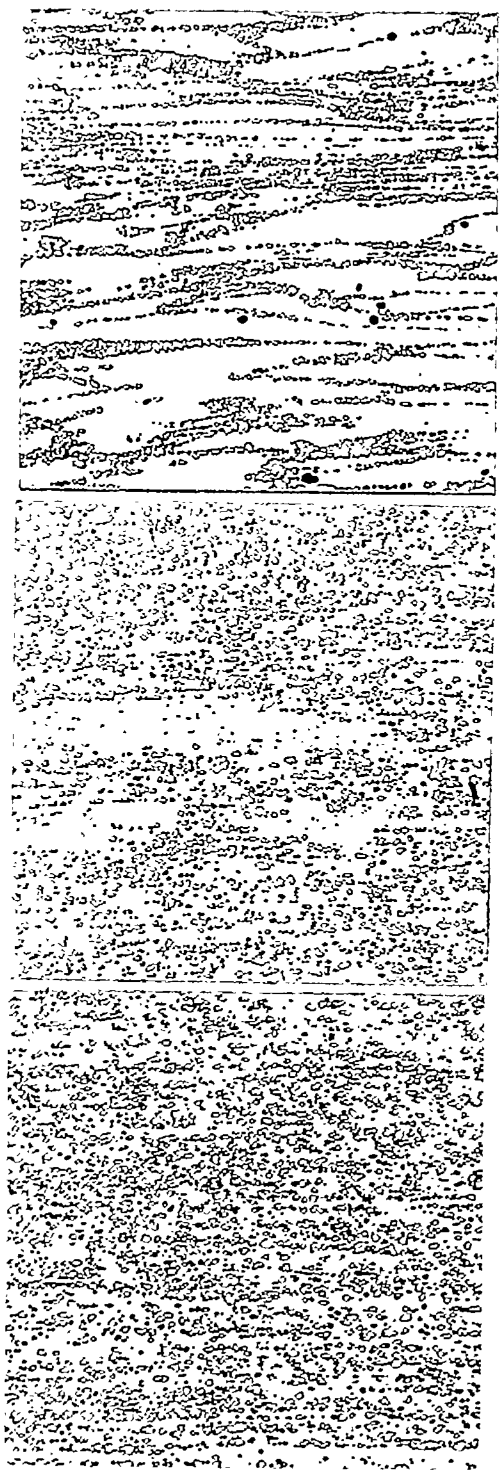


Figure 5.- Effect of extrusion speed and temperature on room-temperature tensile properties.



(a) Heat A2465; center of a longitudinal section from a 1- by 1-inch extrusion; reduction 7:1, 85.9 percent.

(b) Heat A2983; center of a longitudinal section from a 3/4-inch-diameter extrusion; reduction 16:1, 93.75 percent.

(c) Heat A2986; center of a longitudinal section from a 1/2-inch-diameter extrusion; reduction 37:1, 97.22 percent.

Figure 6.- Microstructure of EM-62 magnesium alloy after extrusion reductions of 85.9, 93.75, and 97.22 percent. Unetched, as-extruded. 100X.

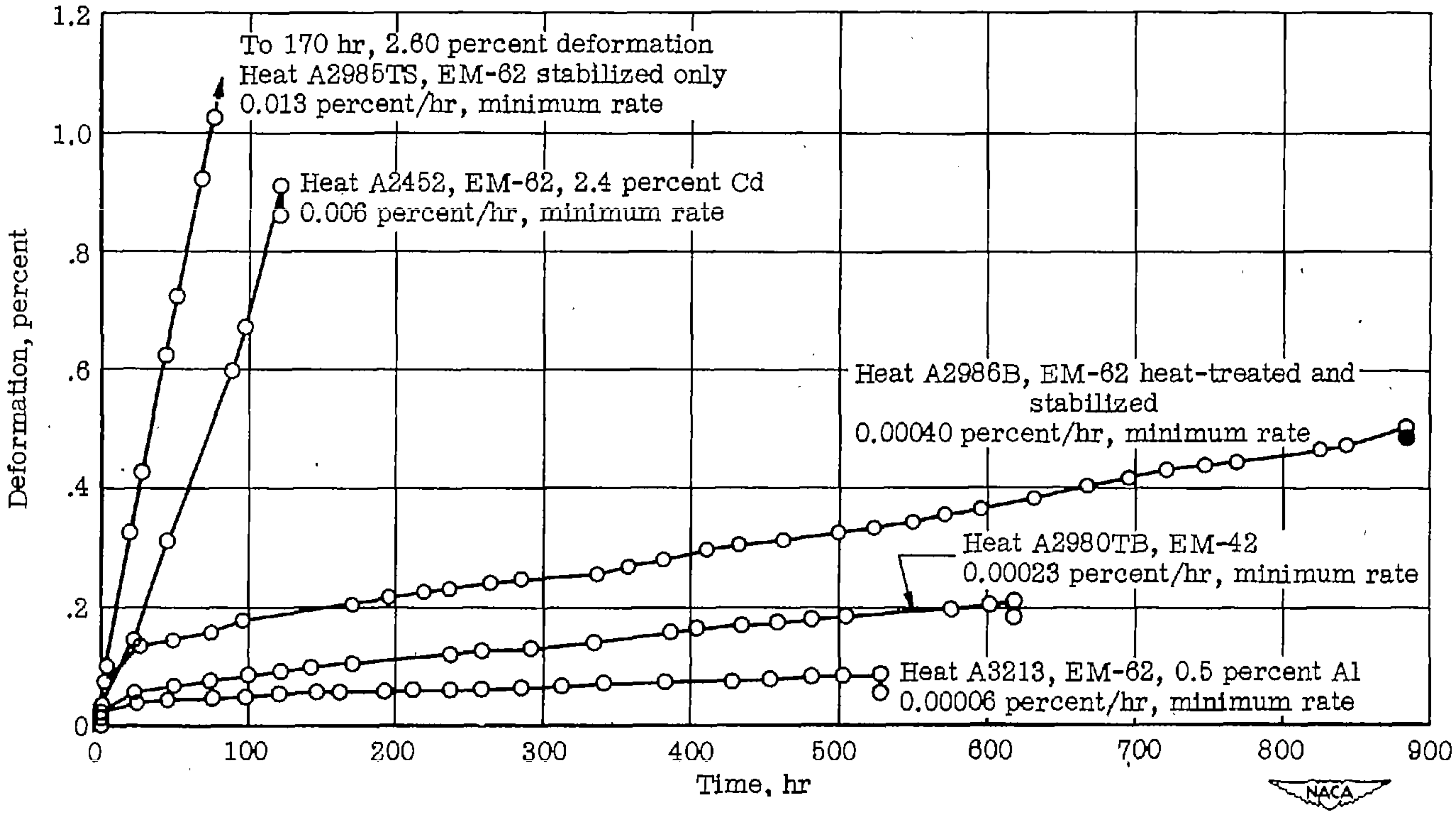


Figure 7.- Time-deformation curves of magnesium-cerium extruded alloys at 600° F and a 1300-psi stress.

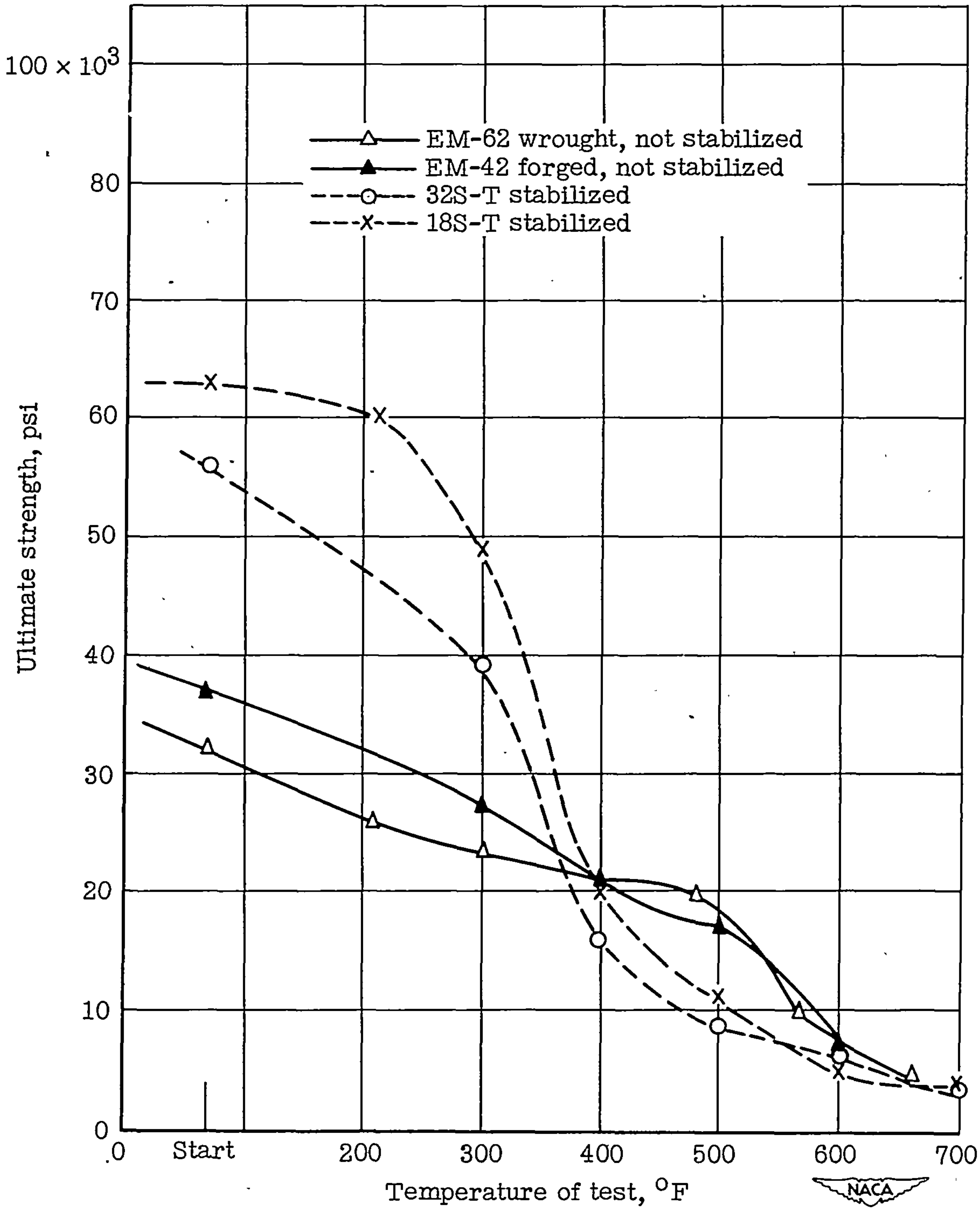


Figure 8.- Effect of temperature on ultimate strength of two magnesium-cerium alloys (solid lines) and two aluminum alloys (dashed lines).

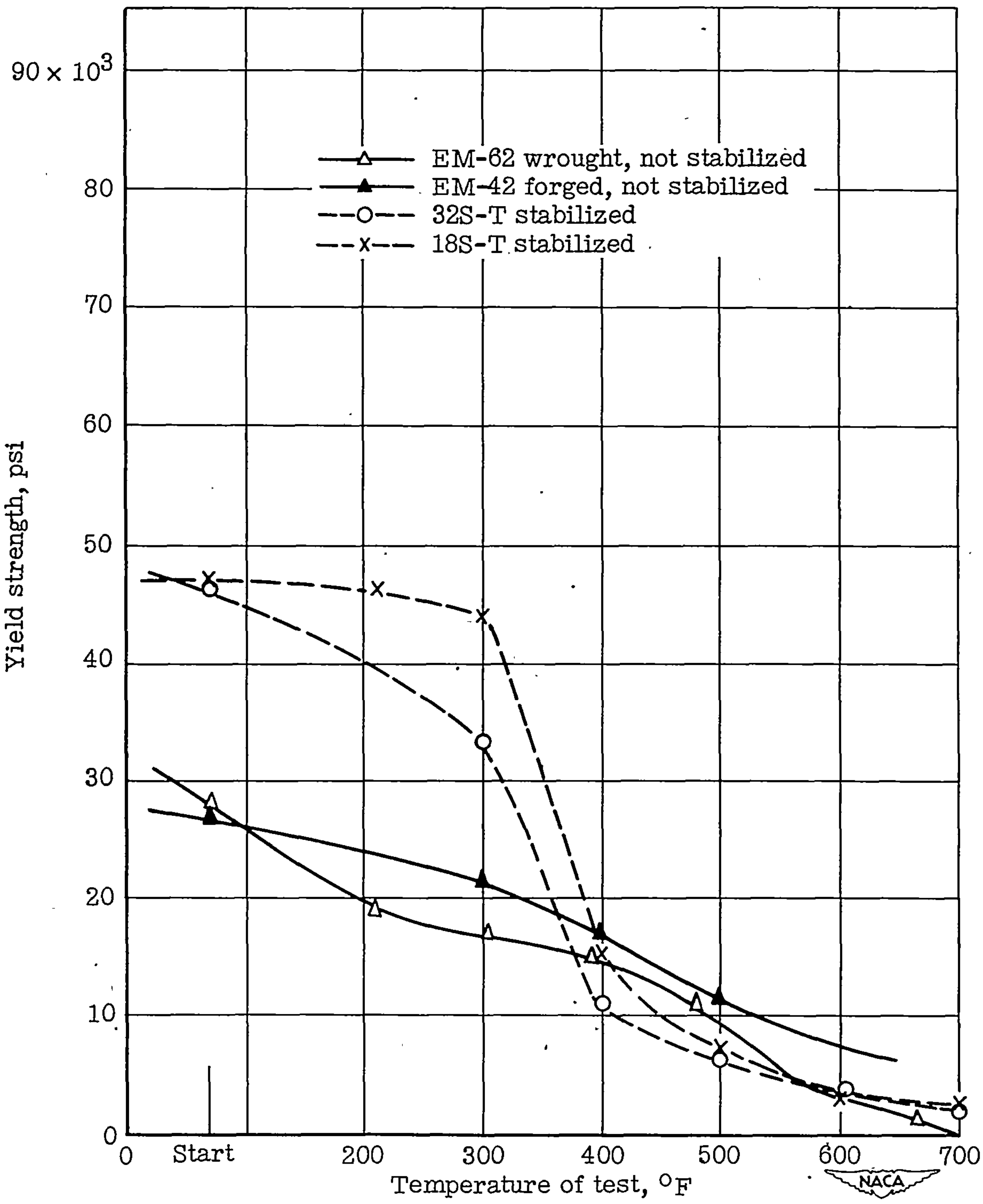


Figure 9.- Effect of temperature on yield strength of two magnesium-cerium alloys (solid lines) and two aluminum alloys (dashed lines).

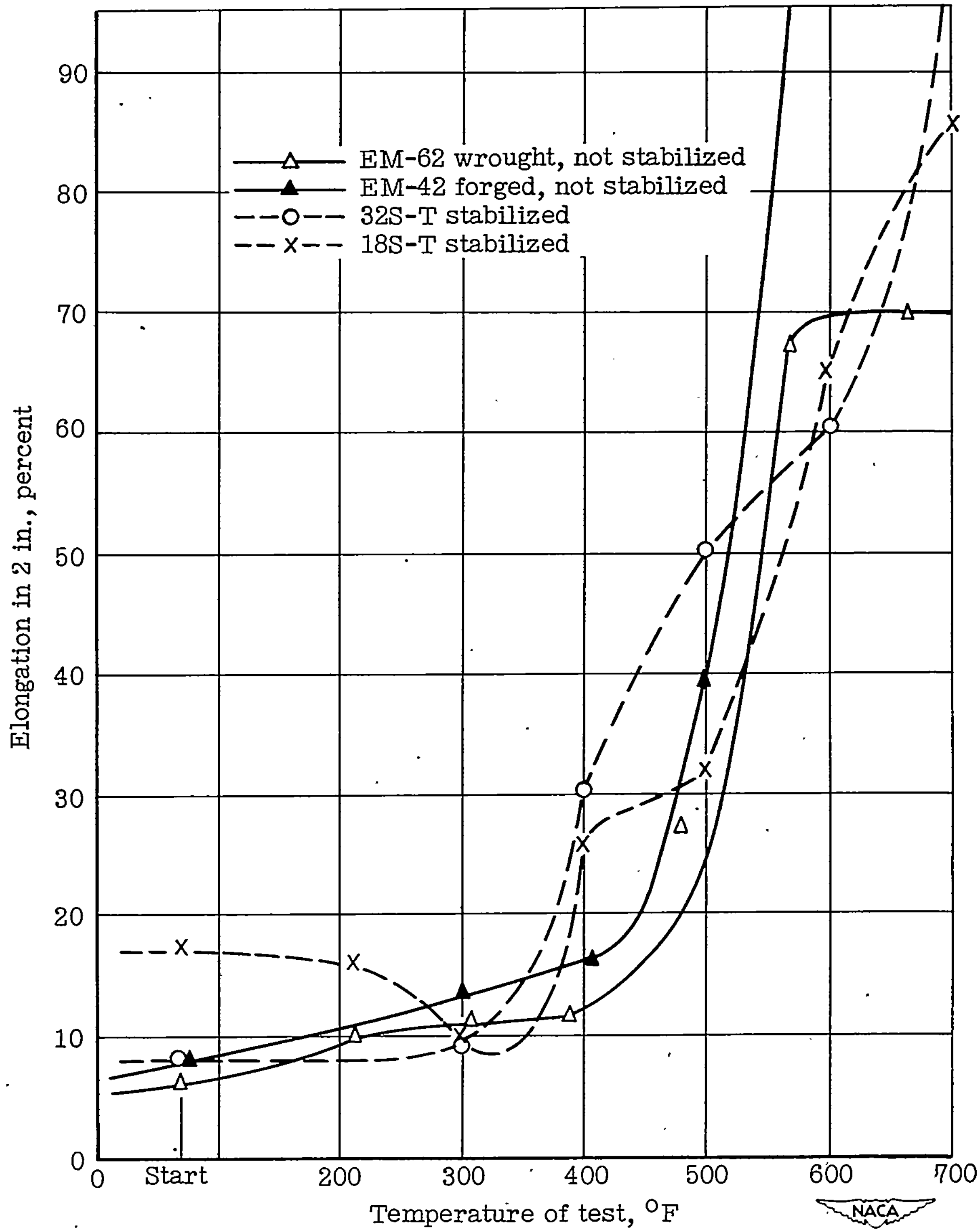


Figure 10.- Effect of temperature on elongation of two magnesium-cerium alloys (solid lines) and two aluminum alloys (dashed lines).

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